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Urban Greening and Reforestation

Edited by Khalid Rehman Hakeem



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IntechOpen Book Series

Sustainable Development

Volume 46

Aims and Scope of the Series

Transforming our World: the 2030 Agenda for Sustainable Development endorsed by United Nations and 193 Member States, came into effect on Jan 1, 2016, to guide decision making and actions to the year 2030 and beyond. Central to this Agenda are 17 Goals, 169 associated targets and over 230 indicators that are reviewed annually. The vision envisaged in the implementation of the SDGs is centered on the five Ps: People, Planet, Prosperity, Peace and Partnership. This call for renewed focused efforts ensure we have a safe and healthy planet for current and future generations.

This Series focuses on covering research and applied research involving the five Ps through the following topics:

1. Sustainable Economy and Fair Society that relates to SDG 1 on No Poverty, SDG 2 on Zero Hunger, SDG 8 on Decent Work and Economic Growth, SDG 10 on Reduced Inequalities, SDG 12 on Responsible Consumption and Production, and SDG 17 Partnership for the Goals
2. Health and Wellbeing focusing on SDG 3 on Good Health and Wellbeing and SDG 6 on Clean Water and Sanitation
3. Inclusivity and Social Equality involving SDG 4 on Quality Education, SDG 5 on Gender Equality, and SDG 16 on Peace, Justice and Strong Institutions
4. Climate Change and Environmental Sustainability comprising SDG 13 on Climate Action, SDG 14 on Life Below Water, and SDG 15 on Life on Land
5. Urban Planning and Environmental Management embracing SDG 7 on Affordable Clean Energy, SDG 9 on Industry, Innovation and Infrastructure, and SDG 11 on Sustainable Cities and Communities.

The series also seeks to support the use of cross cutting SDGs, as many of the goals listed above, targets and indicators are all interconnected to impact our lives and the decisions we make on a daily basis, making them impossible to tie to a single topic.

Meet the Series Editor



Usha Iyer-Raniga is a professor in the School of Property and Construction Management at RMIT University. Usha co-leads the One Planet Network's Sustainable Buildings and Construction Programme (SBC), a United Nations 10 Year Framework of Programmes on Sustainable Consumption and Production (UN 10FYP SCP) aligned with Sustainable Development Goal 12. The work also directly impacts SDG 11 on Sustainable Cities and Communities. She completed her undergraduate degree as an architect before obtaining her Masters degree from Canada and her Doctorate in Australia. Usha has been a keynote speaker as well as an invited speaker at national and international conferences, seminars and workshops. Her teaching experience includes teaching in Asian countries. She has advised Austrade, APEC, national, state and local governments. She serves as a reviewer and a member of the scientific committee for national and international refereed journals and refereed conferences. She is on the editorial board for refereed journals and has worked on Special Issues. Usha has served and continues to serve on the Boards of several not-for-profit organisations and she has also served as panel judge for a number of awards including the Premiers Sustainability Award in Victoria and the International Green Gown Awards. Usha has published over 100 publications, including research and consulting reports. Her publications cover a wide range of scientific and technical research publications that include edited books, book chapters, refereed journals, refereed conference papers and reports for local, state and federal government clients. She has also produced podcasts for various organisations and participated in media interviews. She has received state, national and international funding worth over USD \$25 million. Usha has been awarded the Quarterly Franklin Membership by London Journals Press (UK). Her biography has been included in the Marquis Who's Who in the World® 2018, 2016 (33rd Edition), along with approximately 55,000 of the most accomplished men and women from around the world, including luminaries as U.N. Secretary-General Ban Ki-moon. In 2017, Usha was awarded the Marquis Who's Who Lifetime Achiever Award.

Meet the Volume Editor



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Preface

Amid rapid urbanization and escalating climate challenges, cities face critical issues such as urban heat islands, air pollution, biodiversity decline, and diminished human well-being. This volume, *Urban Greening and Reforestation*, assembles advanced research and evidence-based strategies to foster resilient, sustainable urban ecosystems. The book integrates contributions from international scholars. It examines innovative approaches such as urban afforestation, vertical greening systems, native species integration, and ecosystem-based adaptation. Every chapter is unique, reflecting the experience and scholarly intellect that contribute to the field's understanding. While acknowledging persistent challenges, such as limited land availability, funding constraints, maintenance requirements, species selection in harsh urban conditions, and ensuring equitable distribution, the book emphasizes interdisciplinary collaboration, policy integration, community engagement, and adaptive management to overcome barriers and achieve long-term success.

This work aims to inform policymakers, planners, and researchers about advancing equitable, greener urban futures. I extend sincere appreciation to all contributors for their invaluable efforts, timeless contributions, meticulous research, and result-oriented discussions, which have significantly enriched the quality of this volume.

Khalid Hakeem

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Section 1

Interdisciplinary Approaches
to Urban Greening

Chapter 1

Performance Evaluation of Urban Green Infrastructure

Ting Wang and Yunying Ren

Abstract

Recognizing the critical role of urban green infrastructure (UGI) and its comprehensive performance evaluation in promoting high-quality, green, and low-carbon urban development, this chapter develops a multi-level, scientific, and systematic UGI evaluation framework through multidimensional assessment models. Building on open-source data, we establish a geo-spatial database for the study area and integrate quantitative evaluation tools, including InVEST, ArcGIS, and big data analytics. This methodology enriches the evaluation approach for green infrastructure, providing actionable insights for optimizing UGI systems.

Keywords: urban green infrastructure, performance evaluation system, open-source data, evaluation model, performance indicators

1. Introduction

In the context of urban ecological civilization development, cities are actively exploring the “Lucid Waters and Lush Mountains are Invaluable Assets [1]” (LWIA) ecological development path to achieve high-quality green and low-carbon growth goals. The urban green infrastructure (UGI) comprehensive performance evaluation plays a crucial role in this process. UGI refers to an interconnected network [2, 3] of natural, semi-natural, and artificial open green spaces, forests, wetlands, and water bodies within and around urban areas. This system protects ecosystem services and benefits both humans and biodiversity [4]. From an integrated landscape perspective, UGI achieves organic integration between constructed environments and natural green spaces through complete ecological network design, delivering environmental benefits like carbon sequestration, oxygen release, and biodiversity conservation, along with broader social and economic advantages. Therefore, conducting comprehensive UGI evaluations and optimizing green infrastructure (GI) networks serve as vital approaches to address urban ecological challenges, enhance living quality, and promote green, low-carbon development in urbanized contexts. This chapter analyzes UGI’s essence and performance framework, establishing a multi-tiered, scientific, and systematic evaluation system to enrich methodologies for UGI assessment and optimization, providing actionable insights for urban greening initiatives.

2. Current situation and theoretical basis of UGI performance evaluation research

2.1 Research status

Current UGI research focuses not only on theoretical frameworks and methodologies but also increasingly emphasizes the comprehensive benefits [5, 6] of UGI's ecological, social [7, 8], and economic values, with particular emphasis on quantitative modeling [9]. This approach enhances precision and relevance in addressing environmental challenges [10]. Scholars like Austin [11] and Pauleit [12] have established evaluation systems [13, 14] based on ecological and health indicators, while documents such as the "EU Green Infrastructure Benefit Assessment Model" provide foundational support. However, existing frameworks lack clarity regarding the coupling relationships between UGI network structures and composite functions and are limited by conventional evaluation methods and data sources. Building on this context, our study expands the conceptual scope of UGI, clarifies its structural–functional relationships, and employs open-source data and quantitative models to develop a multi-tiered, scientifically rigorous, and systematic performance evaluation system for UGI.

2.2 Theoretical basis

According to the definition of UGI, it can be found that UGI is a network system with landscape structure integrity and functional complexity. The interpretation of UGI connotation by landscape ecology theory and social ecology theory, as well as the intervention of UGI performance evaluation hierarchy and dimension, play an important role.

2.2.1 Related theories

Landscape ecology theory, proposed by German geographer C. Troll in 1939, emphasizes the interactions between spatial patterns, ecological processes, and scales, while introducing the "patch-walkway-matrix" model. This framework provides a comprehensive conceptual basis for studying landscape spatial structures and ecological processes, while offering a "spatial language" to describe landscape composition, functionality, and dynamics. The green infrastructure network structure of "small plots-connecting corridors-network centers" proposed in this study, along with its evaluation metrics and methodological approaches, draws inspiration from this model.

Social ecology theory describes the interdependent and complementary relationship between natural and human societies as a "socio-economic-natural composite ecosystem." Its core proposition is that establishing mutually balanced and complementary mechanisms among social, economic, and natural subsystems within this ecosystem ensures its sustainable and healthy development while guaranteeing economic benefits and social–ecological win-win outcomes [15]. As a green network connecting artificial spaces with natural ecological areas, UGI aims to reshape human–nature connections and ensure harmonious coexistence between human settlements and natural ecosystems. This aligns with the core tenets of social ecology theory, where the proposed socio-economic-natural composite ecosystem constitutes both the essence and functional framework of UGI.

2.2.2 UGI feature

Through the definition and related research basis of UGI, it can be seen that UGI has multiple types in structure – “network center-connection corridor-small site” – and multi-functionality in function – “ecological-social-economic” characteristics (**Figure 1**).

Network centers primarily refer to large, intact natural habitat patches with high ecological quality that are minimally disturbed by human activities. Connectivity corridors serve as pathways and spaces connecting various network centers and small habitats, facilitating ecosystem transmission and delivery. Small habitats, on the contrary, are smaller ecological patches that act as stepping stones in ecological circulation processes.

The universality and complexity of the structure of UGI determine its diversity and complexity of functions, which are mainly reflected in the fact that UGI not only has ecological functions but also has social functions (including culture) and economic functions derived from ecological functions (**Table 1**).

2.2.3 UGI analysis of the connotation of UGI performance evaluation

This study positions UGI as an integrated, complex, and systematic “landscape-ecological-social-economic composite system” that provides a holistic approach to addressing urban ecological challenges. The core objective is to establish a comprehensive performance evaluation framework for UGI systems based on their integrated “landscape-ecological-social-economic” functional benefits. This framework will assess the effectiveness of UGI network systems, identify existing issues and their root causes, thereby providing scientific evidence for their restoration and optimization.

The comprehensive performance evaluation of UGI refers to a quantitative approach that measures its three core benefits: landscape structure, ecological environment, and socio-economic outcomes. This evaluation quantifies the actual effects of UGI elements in delivering ecological, social, and economic benefits to urban areas through their multifaceted functions, essentially providing a spatial representation of the index’s overall effectiveness.

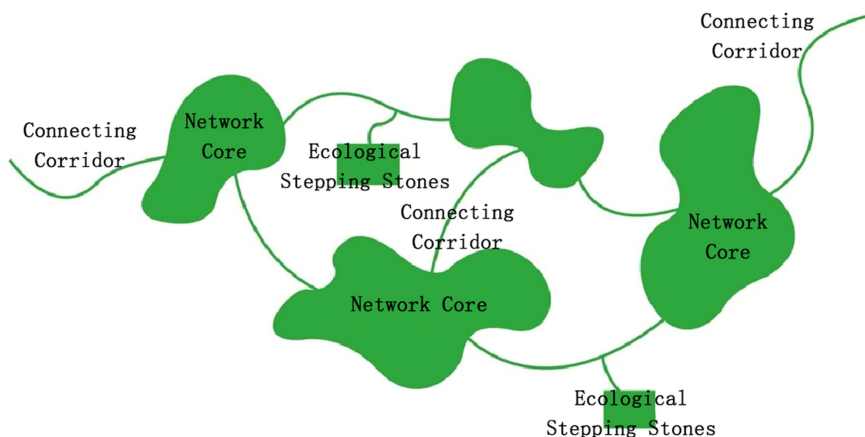


Figure 1.
Schematic diagram of the UGI structure. Source: Author’s illustration.

GI functional classification	Specific function description
Ecological function	Mitigation of climate change
	Improve air quality
	Hydrological regulation
	Carbon fixation and oxygen release
	Improve soil quality
	Reduce noise
	Biodiversity protection
	Waste decomposition and nutrient cycling
Landscape structure function	Maintain the integrity of landscape pattern
	Create a good landscape environment
	Improve corridor connectivity
Social (cultural) functions	Improve your health
	Improve mental health
	Provide recreational facilities
	Improve green space accessibility
	Outdoor space for education and research
	Reduce crime and crime fear
	Enhance attachment and sense of belonging to the local area
Economic function	Make the city more attractive
	Increase land value
	Create jobs
	Increase the income of related industries
	Reduce the cost of managing energy consumption (e.g., reducing carbon emissions, removing pollutants, managing floods)

Source: Author's own drawing.

Table 1.
Summary of the functions of UGI.

2.3 UGI comprehensive performance evaluation framework

The UGI performance evaluation framework proposed in this study establishes four dimensions for assessing UGI performance: landscape structure, ecological environment, social benefits, and economic benefits. These four dimensions encompass two evaluation levels: landscape structure and functional benefits. Specifically, landscape structure serves as the foundation for functional benefits. The structural integrity and health of UGI directly determine its comprehensive effectiveness. Through strategic organization and layout of various elements, multiple functional benefits can be achieved. Functional benefits reflect the structural state of landscape architecture. When issues arise with UGI's functional benefits, it indicates structural fractures or fragmentation in the landscape architecture, which serves as a critical method for evaluating its structural efficiency.

Therefore, based on the characteristics and connotation of UGI, a comprehensive performance evaluation system of UGI is constructed from two levels: landscape structure and functional benefit, and four dimensions of landscape structure, ecological environment, social and economic performance, and corresponding evaluation factors are selected for each dimension (**Figure 2**).

3. Construction of UGI performance evaluation system

This chapter constructs the UGI performance evaluation system based on the principles of objectivity, scientific rigor, operability, systematic hierarchy, and the integration of quantitative and qualitative approaches. By utilizing easily accessible open-source data and incorporating multiple quantifiable evaluation models such as INVEST, MSPA, MCR, and POI, the system aims to scientifically and accurately assess the comprehensive effectiveness of UGI implementation.

3.1 Factor and index selection

This study leverages the structural complexity and functional integration characteristics of UGI to establish evaluation factors at two levels: landscape structure and functional benefits (see **Table 2**). This approach enables a comprehensive and scientific assessment of Fengdong New City's green infrastructure performance, considering both its role as a physical spatial foundation and its practical impacts across ecological, social, and economic dimensions. Through bibliometric analysis and comparative studies, we identified high-frequency evaluation indicators in relevant literature (see **Table 3**), ultimately selecting assessment metrics from four dimensions: landscape structure, ecological environment, social impact, and economic performance (see **Tables 4 and 5**).

3.2 Index weighting

In the indicator system, the weight levels of each metric objectively reflect their relative importance. This study employs a combined weighting method, calculating weights through entropy weighting and then refining them using the Delphi method. This approach not only addresses the lack of objectivity in subjective weighting methods but also corrects the flaw in objective weighting methods that sometimes disregard decision-makers' subjective intentions when determining weights. Ultimately, this results in weight values that are both objective and aligned with the UGI comprehensive performance evaluation objectives.

3.3 Evaluation method

As an important carrier of urban sustainable development, the scientific evaluation of UGI needs to build a multi-dimensional methodological system. According to the evaluation objectives and technical characteristics, the existing evaluation methods can be divided into four categories (see **Table 6**):

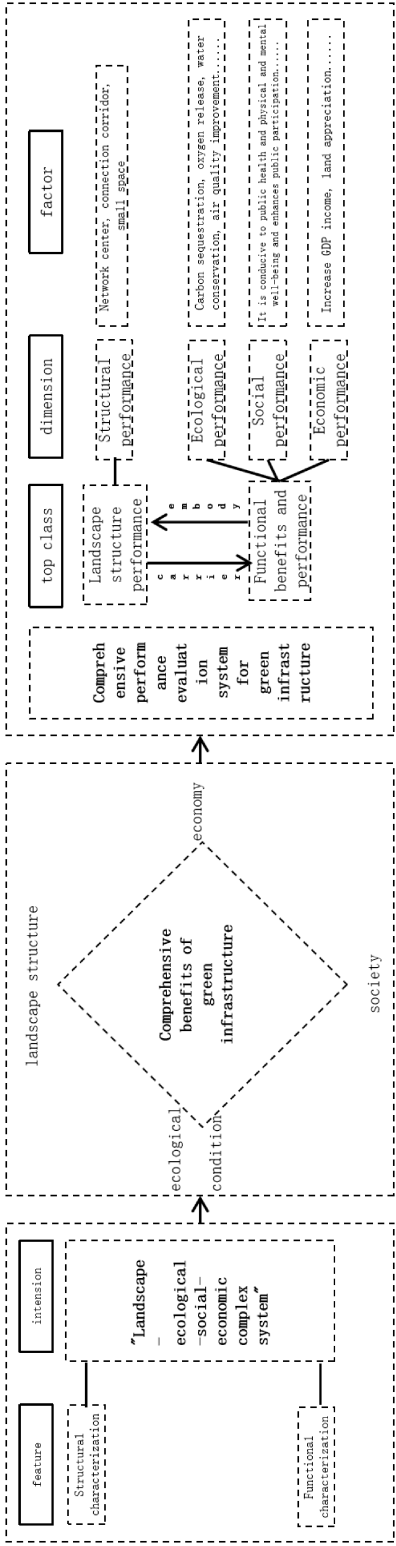


Figure 2.
UGI comprehensive performance evaluation framework. Image source: Author's own drawing.

Functional benefits of green infrastructure	Evaluation factors
Landscape structure performance	Small side court
	Connect the corridors
	Hub
Ecological and environmental performance	Maintain biodiversity
	Improve ambient air quality
	Mitigate the urban heat island effect
	Soil preservation
	Water resource preservation
	Carbon emissions
Social performance	Enhancing urban resilience
	Improve health and well-being
	We will promote the protection of historical and cultural heritage
	Make cities more attractive
	Create beautiful scenery
Economic performance	Enhance environmental value
	Land increment
	Reduce energy consumption

Source: Author's own drawing.

Table 2.
UGI comprehensive performance evaluation factors.

- (1) Structural benefit leading evaluation method
- Morphological spatial pattern analysis (MSPA): Based on the principle of mathematical morphology, the core area and bridge area of GI are identified through grid data analysis to provide a quantitative basis for landscape connectivity assessment.
- Landscape Pattern Index (LPI) method: FRAGSTATS and other software are used to calculate indicators such as patch density and aggregation degree, so as to evaluate the structural efficiency of GI from the perspective of landscape heterogeneity and spatial configuration.
- (2) Ecological benefit dominated evaluation method
- InVEST model: Spatially explicit modeling is used to quantify the value of ecosystem services, which is especially suitable for the monetization assessment of ecological functions such as biodiversity maintenance and water conservation.
- SWMM stormwater model: The runoff reduction efficiency of GI is evaluated through hydrological process simulation, providing a quantitative basis for sponge city construction.
- (3) Social and economic value evaluation technology
- Value analysis method: Through the solar energy value conversion rate (transformity), the different qualities of ecological flow are unified in

First-level indicators	Secondary indicators	Reference documentation
Ecological Index	Microclimate change (e.g., mitigation of the urban heat island effect)	Roghani et al. [16]; Heidt and Neef [17]
	Enhancement of air quality (e.g., lower contaminant release)	CNT [18]; Nowak and Crane [19]
	Greenhouse gas emissions (e.g., avoiding greenhouse gas emissions through cooling)	CNT [18]; Nowak and Crane [19]
	Reduce building heating and cooling energy consumption (e.g., green roofs and walls)	Roghani et al. [16]
	Hydrological regulation (e.g., flow control and flood reduction; water quality regulation)	CNT [18]; Xiao et al. [20]
	Improving soil quality and preventing erosion (e.g., soil fertility and stability)	Pignalosa et al. [21]; McKinney [22]
	Biodegradation and nutrient circulation	Astbury and Rogers [23]
	Noise abatement is attained	CNT [18]; Nettle [24] 2009
Health indicator	Conservation and enhancement of biodiversity (e.g., community, species, habitat conservation)	Threlfall et al. [25]
	Improve physical health (e.g., open-air sports, wholesome food, salubrious environment)	Schipperijn et al. [26]; Subiza et al. [27]
	Enhancing social welfare (e.g., social connections, social cohesion)	Peschardt et al. [28]; Parker and Zingoni de baro [29]; Wood et al. [30]
	Enhancing psychological well-being (e.g., anxiety alleviation)	Arnberger and Eder [31]; Parker and Zingoni de baro [29]; Knobel et al. [32]
	Food supply (e.g., metropolitan farming, edible landscapes, and neighborhood gardens)	Knobel et al. [32]; Clark and Nicholas [33]
Social and cultural indicators	Offer chances for leisure, mobility, and community engagement	Yu [34]
	Improve pedestrian access and network connectivity (e.g., enhance safety and connectivity with other corridors)	Knobel et al. [32]
	Enhance accessibility	Rundle et al. [35]; Du et al. [36]
	Provide outdoor education and research sites	McDonnell et al. [37]
	Reduce crime and fear of crime	Kuo and Sullivan [38]
	Place attachment and belongingness (e.g., cultural significance and symbolic meaning)	Kent et al. [39]; Knobel et al. [32]
	Make the city more attractive	Roghani et al. [16]

First-level indicators	Secondary indicators	Reference documentation
Economic indicator	Add attribute values	Donovan and Butry [40]; Shoup and Ewing [41]
	Increase local economic activity (e.g., tourism, recreation, cultural activities)	Wolf [42]; McPherson and Muchnick [43]
	Save health care costs	Shoup and Ewing [41]; Nobel et al. [32]
	Economic value of service offerings (e.g., unprocessed materials, wood, biofuels, pharmaceuticals, food, clean water, etc.)	Roghani et al. [16]
	The benefits of CO2 reduction and carbon storage	(CNT [17]; Roghani et al. [16])
	The benefits of energy conservation (e.g., reducing the need for cooling and heating)	Jayasooriya et al. [44]; Akbari and Taha [45]
	Air quality improvement value	(McPherson and Muchnick [43])
	Reduce grey infrastructure advantages	(CNT [18]; Xu et al. [46])
	Benefits of flood mitigation	(CNT [18]; Xiao et al. [20])
	Lower automobile expenses through increased walking and cycling	McPherson and Muchnick [43]
Source: Author's own drawing.		

Table 3.
Summary of high-frequency indicators in the relevant literature.

	Evaluation factors	Evaluating indicator
Landscape structure performance	Small side court	Per capita green space area
		Patch number
		Boundary density
		Mean patch area (MPS)
	Connect the corridors	Corridor width
		Corridor density
		Coverage of corridor service radius
		Overall connectivity (IIC)
	Hub	Percentage of total floor space occupied by network centers
		Contagion Index (CONTAG)
		Landscape Shape Index (LSI)
		Shannon Diversity Index (SHDI)
		Network Structure Index
Source: Author's own drawing.		

Table 4.
Selection of landscape structure performance evaluation indicators.

GI function benefits	Evaluation factors	Evaluating indicator
Ecological and environmental performance	Maintain biodiversity	Quality of Habitat Index
	Improve ambient air quality	Excellent air quality rate
	Mitigate the urban heat island effect	Thermal island effect intensity
	Soil preservation	Soil retention
		Vegetation coverage
	Water management	Water conservation capacity
	Carbon sequestration and oxygen production	Carbon fixation and oxygen release
Social performance	Enhancing urban resilience	The proportion of safe green land
		Ecological Resilience index
	Improve health and well-being	Green space activity
		Free access rate of park green space
		Accessibility to GI
	We will promote the protection of historical and cultural heritage	Protection of historical features
	Make cities more attractive	Tourist satisfaction
	Create beautiful scenery	Green ratings
		Aesthetic quality of landscape

GI function benefits	Evaluation factors	Evaluating indicator
Economic performance	Enhance environmental value	Fixed carbon oxygen release value
		Consolidate the value of water sources
	Land increment	GI housing price appreciation rate
	Reduce energy consumption	Surface temperature during peak summer electricity consumption

Source: Author's own drawing.

Table 5.
 Selection of functional benefit evaluation indicators.

Appraisal procedure	Description	Evaluation
InVEST model	The inventory and appraisal of nature's contributions to human survival and quality of life	Ecological benefit
Green Space Index	According to the efficiency of ecosystem services provided by green infrastructure within designated sites, corresponding weights are assigned for comprehensive evaluation	Ecological benefit
MSPA model	Use a small amount of data to objectively evaluate the structural characteristics of green infrastructure	Structural benefits and ecological benefits
Landscape pattern metrics	It is carried out from the aspects of landscape type and level, focusing on process evaluation	Structural benefits and ecological benefits
Value analysis	All forms of matter and energy are converted into a unified unit of energy value by certain conversion coefficients	Ecological benefits, social and economic beneficial result
The weighting factor method	The total value of ecosystem services is calculated by determining the value equivalent of different types of ecosystem services	Ecological benefits, social and economic beneficial result
Mathematical model	The Evaluation Index is designed based on ecosystem services, and the benefit calculation model is constructed	Ecological benefits, social and economic beneficial result
Grey system theory	Quantitative analysis with a small amount of known information	Ecological benefits, social and economic beneficial result
GIS model	The use of computers and digital models to collect and manage spatial distribution data and simulate actual conditions	Ecological benefits, social and economic beneficial result
Function value method	Use monitoring data and information to calculate the total value of ecosystems	Ecological benefits, social and economic beneficial result
i-TREE model CITYgreen model	It is often used in the benefit assessment of forests and trees, which requires a large amount of data	Ecological benefit, economic benefit
SWMM model	A rainstorm assessment and management model, simulating urban hydrological and water quality changes, was developed	Ecological benefits, social and economic beneficial result

Appraisal procedure	Description	Evaluation
Market value method	Use monetary prices directly or indirectly to measure and evaluate benefits	Ecological benefits, social and economic beneficial result
Scenic Beauty Evaluation Method (SBE)	A psychophysical model evaluation method for landscape image scoring	Social and economic benefits
Analytic Hierarchy Process (AHP)	An integrated decision-making methodology that balances quantitative metrics with qualitative assessments	Ecological benefits, social and economic beneficial result
Delphi method	A method in which opinions or judgments are put forward by experts in related fields, and estimates are made	Ecological benefits, social and economic beneficial result
Satisfaction model IPA/ISA method	Residents' psychological perception and evaluation of products or services	Ecological benefits, social and economic beneficial result

Source: Author's own drawing.

Table 6.

Summarizes performance evaluation methods for green infrastructure.

dimension, and the systematic integration and evaluation of energy, material, and economic flow are realized.

Scenic Beauty Evaluation Method (SBE): Using the psychophysical paradigm, a landscape esthetic prediction model is established through public scoring of standardized scene photographs.

Delphi expert method: The index system is constructed through multiple rounds of expert consultation, which is especially suitable for evaluating the cultural heritage conservation value under conditions of data scarcity.

(4) Integrated decision support system

Analytic Hierarchy Process (AHP): Calculate the weights of indicators by constructing a judgment matrix to achieve the multi-dimensional synergistic optimization of ecology, economy, and society.

GIS spatial analysis: it integrates multi-source information, such as remote sensing images and terrain data, and supports spatial decision-making, such as buffer analysis and view field analysis.

The application of various methodologies requires consideration of scale effects: The i-TREE model is suitable for carbon sink calculations at the individual tree scale, the CITY Green model focuses on thermal environment regulation at the neighborhood scale, while the LPI principle applies to regional ecological security pattern construction. Future research should enhance multi-model integration and develop hybrid evaluation frameworks that balance scientific rigor with practical applicability. By comprehensively considering the strengths and limitations of different approaches, we can establish integrated assessment models to improve the comprehensiveness and reliability of evaluation results, thereby facilitating the optimization and sustainable development of UGI systems. Through interdisciplinary collaboration, integrating multidimensional data from ecological,

economic, and social perspectives, we can establish dynamic monitoring and feedback mechanisms to ensure real-time adaptability of assessment models, providing robust support for scientific planning and management of UGI.

3.4 UGI comprehensive performance evaluation system

By integrating the aforementioned methodologies, we have developed a multi-tiered and multidimensional UGI performance evaluation system (see **Table 7**) that comprehensively measures landscape architecture, ecological environment, social impact, and economic benefits. This framework provides scientific evidence for optimizing UGI. Through quantitative analysis, it reveals the interrelationships between these benefits, enabling policymakers to implement targeted strategies that enhance sustainable urban development and achieve harmonious coexistence between humans and nature.

Target layer	The normative layer		Evaluation factors	Evaluating indicator	Nature of indicators
GI comprehensive performance evaluation system	Landscape structure	Landscape structure performance	Small field	Per capita park green space area	Forward direction
				Number of patches	Negative direction
				Boundary density	Negative direction
				Mean patch area (MPS)	Forward direction
			Connect corridor	The corridor width	Forward direction
				Corridor density	Forward direction
				Corridor service radius coverage	Forward direction
				Overall connectivity (IIC)	Forward direction
			Network center	Percentage of total floor area occupied by network center	Forward direction
				Contagion Index (CONTAG)	Forward direction
				Landscape Shape Index (LSI)	Forward direction
				Shannon Diversity Index (SHDI)	Forward direction
				Network Structure Index	Forward direction

Target layer	The normative layer		Evaluation factors	Evaluating indicator	Nature of indicators
	Functional benefits	Ecological environment performance	Maintaining biodiversity	Ecological Quality Index D14	Forward direction
			Improve ambient air quality	Air quality is excellent D15	Forward direction
			Mitigation of urban heat island effect	Thermal island effect intensity	Negative direction
			Soil retention	Soil retention	Forward direction
				Vegetation coverage	Forward direction
			Water conservation	Water conservation	Forward direction
			Carbon sequestration and oxygen production	Carbon storage and oxygen generation quantity	Forward direction
		Social performance	Enhancing urban resilience	The proportion of safe green land	Forward direction
				Ecological Resilience Index	Forward direction
			Improve health and well-being	Green space activity intensity	Forward direction
				Free access rate to park green space	Forward direction
				The accessibility to GI	Forward direction
			Promoting the protection of historical and cultural heritage	Historical preservation protection degree	Forward direction
			Improve the attractiveness of cities	Tourist satisfaction	Forward direction
			Create a beautiful landscape	Green ratings	Forward direction
				Landscape aesthetic	Forward direction
	Economic performance	Economic performance	Enhance environmental value	Carbon fixation and oxygen release value	Forward direction
				Water conservation value	Forward direction
			Land value added	GI Surrounding housing price appreciation rate	Forward direction
			Reduce energy consumption	Surface temperature during peak summer electricity consumption	Negative direction

Source: Author's own drawing.

Table 7.
Evaluation Index system of UGI effect.

4. Conclusions

Through comprehensive evaluation of various indicators to establish the UGI integrated performance assessment system, we found that landscape structure optimization significantly enhanced ecological, social, and economic performance, laying a solid foundation for urban sustainable development. During the construction of this evaluation system, we emphasized the synergistic effects among indicators, which collectively improved urban ecological balance, enhanced residents' quality of life, boosted economic growth, and achieved multi-dimensional win-win outcomes. Further research not only revealed how the optimized UGI network system enhances urban ecology and economy, but also demonstrated that, through this evaluation framework, we can comprehensively assess the specific effectiveness of landscape optimization in improving the ecological environment, enhancing social welfare, and increasing economic benefits. This provides robust data support and a decision-making basis for urban sustainable development strategies. The establishment of this evaluation system marks a more scientific and systematic step forward in urban planning and landscape design.

The UGI performance evaluation system developed in this study addresses pressing global issues such as climate change and biodiversity loss by providing scientific pathways for sustainable urban development through functions including carbon sequestration and oxygen release, urban heat island mitigation, and biodiversity conservation. Against the backdrop of rapid urbanization in China, this system is grounded in the ecological development concept that “lucid waters and lush mountains are invaluable assets” and innovatively constructs a “landscape structure-functional benefits” dual-level, four-dimensional evaluation framework based on landscape ecology and social ecology theories. This framework fills gaps in existing research regarding the clarification of structure-function relationships and quantitative methodologies, demonstrating significant frontier relevance and practical significance. The research findings can be translated through policy formulation, planning and design optimization, and promotion of public participation, providing decision support for green, low-carbon, and high-quality urban development. In the future, with the advancement of multi-model coupling, refinement of dynamic monitoring and feedback mechanisms, and deepening interdisciplinary integration, this evaluation system will further enhance its scientific rigor and practical utility, promoting the optimization and sustainable development of UGI systems worldwide and realizing the vision of harmonious coexistence between humans and nature.

Declaration of competing interest

The authors confirm the absence of any conflicting financial interests or personal relationships that might have influenced the research presented in this chapter.

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Chapter 2

Rooted Narratives: Environmental Humanities and the Cultural Imagination of Urban Greening

Marianna Olivadese

Abstract

Urban greening and reforestation are increasingly recognized as essential strategies to combat climate change, mitigate urban heat islands, and restore ecological balance in cities. Yet, beyond their technical and ecological value, green spaces also embody cultural, symbolic, and emotional dimensions that shape how communities relate to their urban landscapes. This chapter explores the intersection of ecology and culture, framing urban greening initiatives as cultural landscapes that carry memory, meaning, and identity. Drawing from the Environmental Humanities, the chapter examines how trees, parks, and reforested sites function not only as ecological infrastructures but also as carriers of collective narratives and social values. Through selected case studies – including post-industrial reforestation projects, memorial parks, and community-led greening initiatives – the chapter highlights how literature, public art, and participatory design enrich the perception of urban nature. Special attention is given to the challenges of environmental justice, addressing how urban greening can either foster inclusion or contribute to phenomena such as green gentrification. By integrating storytelling, esthetics, and cultural memory with ecological planning, the chapter argues that “planting a tree also means planting an idea.” Urban reforestation is therefore presented not just as an environmental intervention but as a cultural and political gesture – one capable of fostering resilience, civic pride, and a sense of belonging, while supporting sustainable and inclusive urban development.

Keywords: urban greening, reforestation, cultural landscapes, Environmental Humanities, urban resilience, green gentrification

1. Introduction

As global urban populations continue to expand and the impacts of climate change intensify, cities face mounting pressure to implement sustainable and adaptive strategies. Urban greening – through tree planting, reforestation corridors, park creation, pocket gardens, and vertical greenery – emerges not only as ecological infrastructure but also as vital to public health, air quality, climate cooling, biodiversity, and psychological wellbeing.

Yet, while scientific and technical approaches to urban greening rightly emphasize quantifiable metrics – carbon sequestration, pollution reduction, thermal modulation – they risk reducing urban nature to passive infrastructure. Such framings overlook the cultural, symbolic, and affective layers embedded within trees and landscapes. Trees serve as living archives – markers of memory, civic symbols, memorial anchors, and identities shaped by literary, ethical, and social narratives.

This chapter reframes urban trees through the lens of the Environmental Humanities (EH). By foregrounding the symbolic, affective, and narrative dimensions of greening efforts, it shifts the focus beyond functional design to ask: *How do cultural narratives, memory, and identity shape – and are shaped by – urban reforestation?* Using insights from environmental history, cultural geography, critical heritage studies, and literary ecocriticism, it conceptualizes trees as narrative agents embedded in lived geographies.

The central research question guiding this chapter is:

In what ways can the EH deepen our understanding of urban reforestation by uncovering its cultural, symbolic, and narrative dimensions, thereby complementing conventional ecological and infrastructural approaches?

To address this question, the chapter:

- Examines key theoretical perspectives on the cultural significance of urban nature;
- Explores case studies in which trees and green spaces act as symbolic, emotional, and social agents – ranging from memorial plantings to contested tree removals and community-led stewardship initiatives;
- Considers the implications of these cultural readings for urban planning, environmental justice, and participatory governance.

Our argument is that urban trees should be seen not merely as static elements of green infrastructure but as active nodes in living, narrative ecosystems – entities that shape collective memory, identity, and place-based imaginaries. Recognizing this narrative dimension allows for more integrated approaches to urban greening, where quantitative ecological metrics are complemented by qualitative cultural insights, leading to policies and designs that are both environmentally robust and socially meaningful.

By taking this approach, the chapter contributes to interdisciplinary debates linking urban ecology, heritage studies, environmental policy, and cultural geography, advocating for a form of urban greening that is resilient, inclusive, and culturally resonant while supporting climate adaptation and sustainable development.

2. Theoretical framework: Environmental Humanities and urban nature

In the past two decades, the EH have emerged as a critical interdisciplinary response to the limitations of technocratic and resource-driven approaches to ecological challenges. Rooted in fields such as cultural geography, environmental history, literary studies, anthropology, and philosophy, EH posits that today's environmental crises are not only technical or scientific problems but also deeply

cultural and narrative ones [1–3]. The stories we tell – or fail to tell – about nature shape the policies we implement and the futures we imagine.

As scholars like Rob Nixon [4], Donna Haraway [5], and Anna Tsing [6] argue, ecological relationships are as much symbolic and affective as they are functional. The concept of “storied matter” [2] encapsulates this perspective, suggesting that landscapes, plants, and other non-human entities act as narrative agents, capable of embodying histories, memories, and values. An urban tree, for example, is not merely an ecological asset – filtering air or providing shade – but can also serve as a living monument, marking sites of protest, collective memory, or community identity.

One of EH’s key contributions to urban sustainability discourse is its attention to affective ecologies – the emotional and embodied relationships individuals and communities form with their environments [7]. These affective bonds, shaped by practices of care, remembrance, and even grief, often elude conventional policy metrics or cost-benefit analyses. The felling of a neighborhood tree may thus represent not only the loss of an ecosystem service but also a rupture in cultural continuity and a trigger for civic activism [8, 9].

EH also challenges anthropocentric paradigms of urban design by advancing frameworks like multispecies urbanism [10, 11], which foreground the co-agency of humans, plants, and other species in shaping urban life. Cities are not static human constructs but hybrid ecologies, where street trees, pollinators, fungi, and even invasive species participate in the making of everyday spaces. This perspective aligns with recent critiques of the “infrastructural” paradigm of urban greening [12], which tends to reduce urban nature to measurable functions while neglecting its cultural, historical, and narrative dimensions.

Closely related is the growing recognition of cultural ecosystem services (CES) – the non-material benefits derived from nature, such as esthetic pleasure, spiritual value, and a sense of place [13, 14]. While CES frameworks highlight these intangible dimensions, they often lack the methodological tools to fully explore them. EH fills this gap by employing narrative analysis, ethnography, and historical inquiry to uncover the symbolic grammars embedded in landscapes. For example, memorial trees, sacred groves, or community gardens do not merely serve ecological functions but also act as carriers of memory, identity, and social cohesion [15–17].

Consider the case of a reforested brownfield: From a planning perspective, its success might be measured through biodiversity metrics or the remediation of contaminated soil. Yet an EH approach asks different questions: Does the new forest acknowledge the site’s industrial past? Were local communities engaged in its design, perhaps to honor the memories of labor or migration? Does the new planting narrative connect ecological regeneration with cultural storytelling? Far from opposing technical solutions, EH enriches them, ensuring that urban greening projects are not only sustainable but also socially and symbolically resonant.

Ultimately, EH encourages us to view the city as a palimpsest – a living manuscript of overlapping histories, ecologies, and narratives. Urban trees, in this view, are inscriptions that carry collective memories: A linden avenue commemorating historic events, a fig sprouting from a ruin, or a grove planted after a wildfire. These layers of meaning resist standard ecological accounting but are vital to a city’s identity and emotional geography.

By reframing urban greening as both an ecological and cultural practice, EH challenges planners, policymakers, and scholars to ask not only *what* we plant but *why*, *how*, and *with what stories*. In this way, urban reforestation becomes not just an environmental intervention but a narrative act – a process of weaving together memory, identity, and ecological care. This approach opens pathways for more inclusive and participatory forms of urban governance, where sustainable futures are measured not only by ecological resilience but also by the cultural narratives they sustain.

3. Case studies and comparative insights: Transformative urban greening

If we accept that urban nature is not merely ecological infrastructure but also a cultural and narrative phenomenon, we must turn to the spaces where these entanglements become most visible. In cities shaped by crisis, transformation, and informal resilience, greening initiatives often transcend their ecological function, becoming sites of cultural negotiation, affective labor, and symbolic reparation. Urban greening in these contexts is not just about mitigating climate impacts or enhancing biodiversity; it is about rewriting the story of the city itself – turning sites of abandonment, trauma, or neglect into living archives of resilience and collective memory.

This section presents three emblematic case studies, selected for their ability to illuminate what we define as *transformative urban greening*: Practices in which tree planting, community gardening, and urban reforestation operate as acts of memory work, social healing, and place-making. Each case study is drawn from a different geographical and historical context – post-industrial Europe, commemorative landscapes in the United States and Germany, and grassroots initiatives in rapidly urbanizing cities of the Global South. Despite these differences, all cases reveal a convergence of ecological function and cultural meaning.

Methodological approach

The following analysis synthesizes insights from secondary literature, policy and planning documents, and qualitative sources (including interviews, site reports, and artistic representations). Rather than striving for exhaustive coverage, each case was chosen for its illustrative power – demonstrating how cultural, ecological, and affective dimensions of urban greening intersect in distinct but resonant ways.

To ensure a coherent comparative perspective, each case is examined through a triadic interpretive lens grounded in EH:

- Memory: How do greening practices engage with local histories, trauma, or cultural memory?
- Participation: Who initiates and sustains these projects? What forms of collective agency or grassroots involvement are present?
- Justice: How do these efforts address issues of inequality, socio-spatial exclusion, or ecological injustice?

This framework allows us to understand urban greening as a *platform for narrative reconstruction* – a means of reshaping both urban ecosystems and the social stories attached to them.

3.1 Post-industrial reforestation: Ruhrgebiet, Germany

The Ruhr region in Germany is widely recognized as a pioneering model of post-industrial landscape transformation, where abandoned steel and coal infrastructures have been repurposed into ecological parks and cultural heritage sites [18]. Through large-scale initiatives such as the Internationale Bauausstellung (IBA) Emscher Park (1989–1999), a network of linear forests, green corridors, and rewilded industrial ruins was established to regenerate both ecology and local identity [19, 20]. One of the most celebrated sites, Landschaftspark Duisburg-Nord, blends reforestation with industrial archeology, allowing birches, poplars, and wild grasses to reclaim former blast furnaces and rail tracks. Rather than erasing industrial traces, the design by Peter Latz integrates them as a narrative framework, creating a hybrid space where ecological resilience coexists with cultural memory [21–23]. Public participation, cultural events, and heritage tourism play a central role in sustaining the park as a living archive of the Ruhr's industrial past.

3.2 Urban memory parks: 9/11 memorial grove and Tempelhofer Feld

Urban greening can also act as a living memorial. The 9/11 Memorial Grove in New York City, designed by Peter Walker and Michael Arad, features rows of white oak trees as symbols of endurance and renewal. Their seasonal rhythms – blossoming, shedding leaves, and renewal – mirror the emotional cycles of grief and remembrance [24]. The grove is not simply decorative but a ritualized space of collective memory, where trees function as silent witnesses to tragedy and recovery.

Similarly, Tempelhofer Feld in Berlin, a former Nazi-era airport and Cold War site, was reimaged as a vast public park after 2008. It now features meadows, community gardens, and temporary art installations that reflect both the site's complex history and its contemporary role as a democratic, open landscape [25]. Here, greening and cultural memory intersect, with grassroots groups using gardens to create narratives of reconciliation, inclusivity, and civic pride.

Both examples highlight how urban trees and green spaces can mediate between past trauma and future aspirations. Rather than monumentalizing memory through static stone, these landscapes use living materials – trees, grasses, flowers – as dynamic memorials that encourage reflection, dialogue, and resilience.

3.3 Community-led greening in rapidly urbanizing cities

In rapidly urbanizing regions, urban greening often emerges through bottom-up, community-driven efforts, particularly where public resources are limited. In Medellín, Colombia, the “Green Corridors” (*Corredores Verdes*) initiative has transformed degraded urban zones into micro-forests, shaded pedestrian paths, and biodiversity hotspots. This project, widely recognized for reducing local urban heat islands, relies on community participation, social education, and local stewardship, turning greening into a tool for social inclusion and environmental justice [26–28].

In Metro Manila (Philippines), grassroots organizations have mobilized to plant trees along flood-prone rivers, creating community food gardens, medicinal plant areas, and protective green belts [29]. These efforts combine disaster mitigation with cultural storytelling, where trees are often planted during local ceremonies, embedding them into the collective narrative of resilience [30]. Such initiatives underscore the role of local ecological knowledge and collective action in shaping sustainable urban futures.

These initiatives are deeply participatory and narrative-driven: Residents are not passive beneficiaries but co-authors of the landscape, embedding local stories, traditions, and ecological knowledge into the urban fabric [31]. By intertwining ecological function with cultural expression, these projects foster social cohesion and environmental justice, particularly in marginalized neighborhoods often excluded from formal planning [32].

Across these examples, urban greening becomes transformative when ecological functionality is intertwined with cultural meaning [33]. The Ruhrgebiet demonstrates how industrial ruins can evolve into ecological memorials [34]; the 9/11 Memorial Grove and Tempelhofer Feld illustrate how trees can narrate collective trauma and healing [35]; while Medellín and Manila highlight community co-authorship of green spaces as tools of empowerment and justice [36]. By viewing these initiatives through the lens of EH, we recognize that trees and parks are not neutral infrastructure but agents of narrative, identity, and affective connection. This perspective urges urban planners to integrate ecological goals with cultural and social dimensions, ensuring that reforestation strategies are both resilient and meaningfully rooted in local narratives.

4. Storytelling, public art, and participatory design: Greening as cultural infrastructure

Urban greening becomes truly transformative when it transcends the boundaries of ecological intervention and urban policy, emerging instead as a shared cultural narrative. As the preceding case studies illustrate, trees and green spaces are not passive elements of urban infrastructure; they acquire meaning, memory, and symbolic weight through stories, images, rituals, and participatory practices [37, 38, 39]. These mediating forms – literature, public art, and co-design – act as “cultural infrastructures” [40], making the ecological both visible and emotionally resonant.

Contemporary ecocritical literature frequently casts trees and green spaces as protagonists, reinscribing them with agency and symbolic presence [41]. Works such as *The Overstory* [42] or Hope Jahren’s *Lab Girl* [43] invite readers to perceive trees as active witnesses and kin – echoing the EH’s emphasis on “storied matter” [2]. These narratives do not merely describe urban greening; they shape its public perception by framing tree-planting as acts of protest, care, or cultural memory.

Even classical allegories, like Italo Calvino’s *Il barone rampante* [44], offer enduring metaphors of arboreal life as an alternative form of citizenship and spatial negotiation – an interpretive lens echoed in Mediterranean contexts such as Naples, where spontaneous greening and balcony gardens reflect vernacular ecological practices [45]. Literature thus functions as a cognitive and affective scaffold, enabling individuals and communities to “read” urban trees as living texts that weave together history, myth, and future aspirations.

Artistic interventions – murals, sculptures, eco-art, and performative installations – operate as a visual and spatial language that communicates the invisible work of urban ecologies [46, 47]. In places like Medellín, where hillside reforestations intersect with histories of violence and social repair, murals often depict trees as guardians, mothers, or storytellers, transforming green spaces into narrative landscapes of healing and resilience [48]. Similarly, the *Edible Hut* project in Detroit illustrates how art-led greening initiatives can reclaim abandoned lots, blending community gardening with esthetic activism [49].

Public art, in this sense, is not an accessory to environmental planning but a cultural technology that amplifies the political and emotional resonance of green interventions. Through the language of color, form, and symbolism, art allows trees and gardens to function as visible emblems of collective memory and socio-ecological repair.

Participation in urban greening – whether through formal co-design workshops or informal community-led planting – operates as a performative act of place-making [51, 52]. These practices are not limited to functional landscaping but are deeply ritualistic and narrative. Tree-planting ceremonies, for example, often mark pivotal moments – such as commemorations of loss, recovery from disaster, or collective visions of the future. In Medellín, “memory walks” and neighborhood planting events integrate local oral histories with ecological regeneration, producing green spaces that are both lived and storied [53, 54].

In Naples, spontaneous greening – balconies turned into micro-gardens, abandoned plots reclaimed as communal orchards – embodies a form of vernacular design that embeds local knowledge, mythologies, and cultural resilience into the urban fabric [55]. These “everyday ecologies” challenge top-down models of planning by foregrounding care, community ownership, and symbolic attachment.

What emerges from this interplay of literature, art, and participatory practices is a shift in how we understand urban nature. Rather than viewing green infrastructure as a purely technical or ecological system, we recognize it as cultural infrastructure – a narrative scaffold where meanings are negotiated, identities are formed, and collective memories are inscribed [56, 58]. Trees, in this perspective, are not merely carbon sinks or shade providers but living witnesses, entwined with human stories of displacement, resilience, and hope.

In cities like Detroit, Naples, and Medellín, urban greening becomes legible and sustainable only when it is culturally mediated – when communities can see and feel their histories and aspirations reflected in the landscape. This insight is crucial for planners and policymakers: Without cultural embedding – through storytelling, esthetic interventions, and participatory rituals – urban greening risks remaining an abstract technical exercise rather than a shared, lived, and meaningful practice.

5. Planting trees, planting ideas

Urban greening is not only an ecological or technical endeavor; it is, fundamentally, a cultural and narrative act. Trees and green spaces in the city are more than carbon sinks or biodiversity supports: They are living archives of memory and meaning, inscribed with stories of migration, marginalization, care, and transformation [58, 2]. Through the lens of the EH, green infrastructure emerges as a site where ecological functions intersect with cultural narratives, esthetic values, and affective attachments. Case studies from Detroit, Naples, Ruhrgebiet, and Medellín

demonstrate that urban greening is most transformative when it resonates with local history and community identity. In such contexts, planting trees becomes an act of place-making and reimagining belonging, rather than a mere policy response to climate change or urban heat islands [12, 55]. These examples also highlight potential tensions: Top-down greening projects that disregard cultural contexts risk perpetuating inequalities or erasing community memory, reducing green infrastructure to a depoliticized and technocratic solution [59, 60].

To describe a city as “narratively just” is to move beyond traditional notions of distributive or procedural justice – focusing instead on whose stories are visible, whose histories are acknowledged, and whose ways of knowing are integrated into the planning of urban nature [61, 62]. Narrative justice entails that:

- Urban greening initiatives incorporate participatory storytelling tools – such as memory walks, oral history projects, and creative mapping – to ensure that local voices and histories inform the design of green spaces [63, 64].
- Indicators of success include not only ecological metrics (e.g., canopy coverage, biodiversity indices) but also cultural metrics, such as symbolic resonance, community participation, and historical recognition [13].
- Green spaces are recognized as platforms for cultural expression and ecological citizenship, where commemorative plantings, artistic interventions, and rituals of care become part of urban identity-building [65, 56].

EH perspectives suggest that urban trees are not inert components of infrastructure but actors in “narrative ecosystems” – shaping how communities remember the past, inhabit the present, and envision sustainable futures [42, 66]. As such, integrating cultural and narrative dimensions into urban greening is not a luxury but a prerequisite for building resilient, inclusive, and meaningful cities. To operationalize these insights, this chapter proposes several strategies for embedding EH methodologies into planning and governance:

1. Participatory narrative planning

Planners, landscape architects, and policymakers should integrate narrative-based methods – story circles, cultural asset mapping, and citizen ethnographies – into the early stages of green infrastructure design [67]. These tools help uncover place-based meanings and mitigate the risk of erasing local histories.

2. Cultural impact assessments (CIA)

Just as environmental impact assessments (EIA) evaluate ecological effects, CIAs should assess the cultural and symbolic implications of greening projects – particularly in heritage-rich or post-trauma urban areas (UNESCO, 2019).

3. Cross-sector collaboration

Urban greening policies should explicitly involve artists, historians, anthropologists, and local storytellers alongside technical experts [37, 40]. Their expertise ensures that urban forests and parks are emotionally legible and culturally embedded.

4. Policy frameworks for narrative inclusion

Frameworks such as UN-Habitat's Right to the City and UNESCO's Culture|2030 Indicators can guide cities in integrating memory, heritage, and cultural narratives into green planning (UN-Habitat, 2020).

5. Education and capacity building

Planning schools, universities, and professional training programs should promote cultural literacy – teaching future practitioners to combine environmental planning with narrative methods, critical geography, and EH perspectives [51, 56].

By acknowledging that “to plant a tree is also to plant an idea,” this chapter advocates for urban greening strategies that merge ecology with culture. This integrated approach enhances not only environmental resilience but also social cohesion and symbolic belonging, fostering cities that are sustainable, storied, and inclusive.

6. Conclusion: Toward storied and sustainable urban futures

This chapter has argued that urban greening and reforestation must be understood as cultural as well as ecological interventions. By applying the lens of the EH, we have shown that trees and green spaces are not merely technical solutions to climate change or urban heat islands, but also living archives of memory, identity, and collective imagination. As such, the success of urban greening initiatives depends not only on ecological performance but also on their cultural legibility, symbolic resonance, and social inclusiveness.

The case studies of Detroit, Naples, and Medellín illustrate that when urban greening aligns with local histories, affective attachments, and participatory practices, it becomes a tool for social healing and narrative reconstruction. Conversely, top-down or purely technical projects risk erasing memory, reinforcing inequalities, or reducing green infrastructure to a depoliticized backdrop.

A key insight emerging from this chapter is the need for “narrative justice” – an approach that recognizes that urban environmental justice is not only about access to green space but also about whose stories, memories, and cultural values shape that space. In this sense, to plant a tree is also to plant an idea: Every green intervention carries narratives of the past and aspirations for the future.

Moving forward, the integration of cultural and narrative methodologies – such as participatory storytelling, creative mapping, and cultural impact assessments – should become standard in urban planning. Cross-sector collaboration with artists, local historians, and humanists can help create urban landscapes that are not only ecologically resilient but also culturally meaningful and emotionally resonant.

Finally, urban greening should be understood as part of a broader “cultural infrastructure” – a framework that merges technical expertise with narrative imagination, ecological science with public art, and policy with community memory. By embracing this integrated vision, cities can transform reforestation and green space planning into opportunities for storytelling, social cohesion, and heritage-building, fostering sustainable and inclusive futures for both people and nature.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 3

Harnessing Green Enzyme Extraction for Sustainable Urban Greening

Muhammad Ayyub Muhammad

Abstract

Urban greening mitigates climate change, enhances biodiversity, and improves urban quality of life. This chapter explores green enzyme extraction methods namely, aqueous two-phase systems (ATPS), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE) to obtain plant-based enzymes for sustainable urban greening. These eco-friendly techniques reduce chemical and energy use, aligning with United Nations Sustainable Development Goals. Using *Moringa oleifera* and *Tithonia diversifolia*, we evaluated extraction efficiency and environmental impact for enzymes promoting soil health and reforestation. UAE and MAE achieved >90% cellulase recovery via rapid cell wall disruption, while ATPS reduced carbon emissions by 30% through solvent recycling, ideal for industrial scaling. Applied to urban soils, extracted enzymes enhanced microbial activity and plant growth. UAE-derived cellulase increased soil microbial biomass by 50%, and ATPS-extracted protease boosted root elongation by 180% in saplings. These results highlight the role of green enzyme extraction in addressing soil degradation and space scarcity. ATPS, UAE, and MAE support circular economy principles by repurposing plant biomass, reducing reliance on synthetic fertilizers. Future research should optimize scalability across diverse urban climate and integrate these methods into reforestation frameworks to maximize ecological benefits.

Keywords: aqueous two-phase systems (ATPS), ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), *Moringa oleifera*, *Tithonia diversifolia*, cellulase, protease

1. Introduction

The rapid expansion of urban landscapes has precipitated profound ecological disruptions, including the fragmentation of green spaces, degradation of air quality, and the intensification of urban heat island effects, all of which contribute to

accelerating biodiversity loss [1, 2]. In response, urban greening and reforestation initiatives have emerged as critical strategies to mitigate these anthropogenic impacts. By reintroducing vegetation into built environments, such initiatives aim to restore ecosystem services, notably carbon sequestration, microclimate regulation, and habitat provision, while fostering socioecological resilience and enhancing human well-being [3, 4].

Central to these efforts is the application of biocatalytic processes, particularly enzyme-driven interventions, to optimize soil health and stimulate plant growth in urbanized settings. Enzymes such as laccases, peroxidases, and cellulases play pivotal roles in organic matter decomposition, nutrient cycling, and pollutant degradation, thereby supporting the establishment and maintenance of urban green infrastructure. However, conventional enzyme production methods often depend on energy-intensive extraction protocols and hazardous solvents, which paradoxically contravene the sustainability objectives they seek to advance [5]. For instance, petroleum-derived solvents and high-temperature processing not only escalate carbon footprints but also generate toxic by-products, undermining the ecological benefits of urban greening projects.

To address this paradox, emerging research advocates for the adoption of green extraction technologies such as ultrasound-assisted extraction (UAE) or microwave-assisted extraction (MAE), aqueous two-phase systems (ATPSs), and enzyme-assisted bio-recovery to sustainably harness biocatalysts from renewable biological waste streams. These methods align with circular bioeconomy principles by minimizing resource consumption, eliminating toxic inputs, and valorizing organic by-products (e.g., agricultural residues, lignocellulosic waste) as enzyme sources. Integrating such innovations into urban greening frameworks could catalyze a paradigm shift, enabling cities to simultaneously combat environmental degradation, reduce reliance on synthetic inputs, and achieve climate resilience targets.

This chapter delves into advanced green extraction methodologies for enzymes, emphasizing techniques such as ATPS, UAE, and MAE. These approaches prioritize the use of environmentally benign solvents and enhance energy efficiency, thereby minimizing the ecological footprint of enzyme recovery processes [6, 7]. By employing such sustainable extraction technologies, the production of plant-derived enzymes can be optimized to support urban greening initiatives effectively. These enzymes play a vital role in enhancing soil microbial activity, nutrient cycling, and the successful establishment of trees and vegetation within urban landscapes [8].

By integrating these innovative biotechnological strategies, this chapter contributes to urban greening and reforestation efforts, illustrating how eco-friendly enzyme extraction methods can underpin resilient and sustainable urban ecosystems. This aligns closely with global sustainability frameworks and objectives, including the United Nations Sustainable Development Goals, by promoting circular bioeconomy principles and reducing reliance on conventional, resource-intensive extraction techniques [9].

Green extraction methods such as aqueous two-phase systems (ATPS), ultrasound-assisted extraction (UAE), and microwave-assisted extraction (MAE), align with green chemistry principles by minimizing chemical use and energy consumption. These techniques support the biorefinery concept,

repurposing plant biomass like *Moringa oleifera* and *Tithonia diversifolia* into enzymes for soil remediation and urban reforestation, fostering sustainable urban ecosystems [10].

2. Experimental design and methodology

2.1 Experimental design

To evaluate the effectiveness of sustainable enzyme extraction techniques applicable to urban greening, a comparative experimental study was undertaken, focusing on three environmentally benign methods: ATPS, UAE, and MAE. These techniques were strategically chosen based on their demonstrated low environmental footprint, reduced solvent consumption, and scalability potential for industrial applications [1, 2]. The study targeted the extraction of key plant-derived enzymes – cellulases and proteases – from species highly relevant to urban reforestation efforts, namely *Moringa oleifera* Lam. (*Moringa*/Drumstick tree) and *Tithonia diversifolia* (Hemsl.) A. Gray (Mexican sunflower). These species are favored in urban afforestation projects due to their adaptability to disturbed soils, rapid growth, and contribution to soil stabilization and nutrient cycling within urban ecosystems. Each extraction method was optimized for parameters such as solvent composition, temperature, extraction time, and energy input to maximize enzyme yield and activity while maintaining eco-friendly operational conditions. The resulting enzyme extracts were subsequently characterized for activity, purity, and stability to assess their suitability for enhancing soil microbial dynamics and supporting vegetation establishment in urban environments [3].

2.1.1 Aqueous two-phase systems (ATPS)

The ATPS employed in this study utilized a biocompatible polymer–salt combination of polyethylene glycol (PEG-4,000) and ammonium sulfate to achieve enzyme partitioning without the use of harmful organic solvents. This approach aligns with green chemistry principles by minimizing environmental impact while maintaining extraction efficiency. The protocol was adapted from Chemat et al. [6], employing a system comprising 20% (w/w) PEG-4,000 and 15% (w/w) ammonium sulfate, buffered at pH 7.0 to optimize enzyme stability and phase separation performance. Enzyme activity was measured using a spectrophotometer at 540 nm for cellulase and 280 nm for protease, with yields recorded after 30 minutes of phase separation.

2.1.2 Ultrasound-assisted extraction (UAE)

UAE was conducted using a 20 kHz ultrasonic probe operating at a power intensity of 100 W/cm², following the methodology described by Zhang et al. [7]. Plant material was homogenized and suspended in an aqueous buffer solution to facilitate enzyme release under mild, environmentally friendly conditions. The extraction process was carried out for 15 minutes at a controlled temperature of 25°C to prevent thermal denaturation of enzymes while maximizing cavitation effects that disrupt plant cell walls and enhance mass transfer. Post-extraction, enzyme yield and

activity were quantitatively assessed to determine the efficacy of UAE relative to conventional solvent-based extraction methods. Particular attention was given to energy consumption metrics, highlighting UAE's potential as a more energy-efficient and sustainable alternative for recovering bioactive enzymes from urban greening biomass.

2.1.3 Microwave-assisted extraction (MAE)

MAE was performed using a 2.45-GHz microwave system operating at a power output of 300 W, following the protocol established by Nadar et al. (2018). Extractions were carried out for a brief duration of 5 minutes, with stringent temperature control maintained below 40°C to prevent thermal denaturation and preserve the functional integrity of the target enzymes. The rapid and uniform heating provided by microwave irradiation facilitated efficient disruption of plant cell matrices, thereby enhancing enzyme release into the extraction medium. Subsequent quantification of enzyme activity enabled evaluation of MAE's effectiveness in comparison to traditional heating methods. Additionally, energy consumption metrics were recorded and analyzed, demonstrating MAE's potential as a time and energy-efficient green extraction technology suitable for sustainable enzyme recovery from urban greening biomass.

2.2 Materials and methodology

2.2.1 ATPS for enzyme extraction

Materials

Polyethylene glycol (PEG-4000, molecular weight 4000 Da) at 20% (w/w) concentration

Ammonium sulfate (analytical grade) at 15% (w/w) concentration

Phosphate buffer (0.1 M, pH 7.0), 50 mL

Fresh *Moringa oleifera* leaf samples (10 g), collected from urban-adjacent sites

UV-Vis spectrophotometer

Procedure

Fresh *Moringa oleifera* leaves (10 g) were harvested and homogenized in 50 mL of phosphate buffer using a blender operated at 10,000 rpm for 5 minutes. The homogenate was subsequently filtered through a 0.45- μ m mesh to remove particulate debris. Polyethylene glycol (PEG-4000) and ammonium sulfate were then added at a ratio of 20:15 (w/w) to the filtrate to form the ATPS. The resulting mixture was stirred at 25°C for 30 minutes at 200 rpm to promote complete phase separation. Following this, the system was centrifuged at 5,000 rpm for 10 minutes at 4°C to separate the distinct phases. The upper enzyme-enriched phase was carefully collected, and enzyme activities were quantified: Cellulase activity was

measured spectrophotometrically at 540 nm using carboxymethyl cellulose as the substrate, while protease activity was determined at 280 nm using casein as the substrate.

All measurements were conducted in triplicate, and enzyme yields were calculated as percentages of the total protein extracted. pH stability was maintained at 7.0 ± 0.1 throughout the procedure using a calibrated pH meter. Phase separation was confirmed through both visual inspection and turbidity analysis.

2.2.2 UAE of enzymes from *Tithonia diversifolia* leaves

Materials

Ultrasonic probe (20 kHz frequency, 100 W/cm² intensity; Sonics VCX-500)

Phosphate buffer (0.1 M, pH 7.0), 50 mL

Fresh *Tithonia diversifolia* leaf samples, 10 g

Centrifuge (Eppendorf 5,810 R)

Procedure

Tithonia diversifolia leaf samples (10 g) were suspended in 50 mL of phosphate buffer and placed in a cooled ultrasonic bath, with the temperature maintained at 25°C. Ultrasonic treatment was applied using a 20-kHz probe operating at 100 W/cm² intensity in pulse mode (5 seconds on, 5 seconds off) for a total duration of 15 minutes. After sonication, the resulting extract was filtered through a 0.45-μm mesh and centrifuged at 6,000 rpm for 5 minutes at 4°C to remove solid residues. The supernatant was collected and analyzed for enzyme activity using previously described spectrophotometric assays. All experiments were performed in triplicate. Energy consumption was recorded via an inline wattmeter. The temperature was continuously monitored using a thermocouple to prevent overheating beyond 40°C, and ultrasonic intensity was validated with a calibration probe to ensure consistent energy delivery.

2.2.3 MAE of enzymes from *Moringa oleifera* leaves

Materials

Microwave system (2.45 GHz frequency, 300 W power; CEM Discover)

Phosphate buffer (0.1 M, pH 7.0), 50 mL

Fresh *Moringa oleifera* leaf samples, 10 g

Temperature probe and centrifuge

Procedure

Moringa oleifera leaf samples (10 g) were mixed with 50 mL of phosphate buffer in a microwave-safe vessel. Microwave irradiation was applied at 300 W for

5 minutes, with an integrated cooling system used to maintain the temperature below 40°C, thereby preventing thermal degradation. Following treatment, the mixture was centrifuged at 6,000 rpm for 5 minutes at 4°C to separate solids from the extract. The supernatant was collected, and enzyme activity was assayed using established spectrophotometric methods. All extractions were carried out in triplicate. Energy consumption and extraction yield were recorded and analyzed. Temperature control was continuously monitored via a temperature probe, and microwave power output was periodically calibrated to ensure reproducibility and prevent enzyme denaturation.

3. Results and discussion

This section evaluates the performance of green enzyme extraction techniques, namely ATPSs, UAE, and MAE, in recovering cellulase and protease from *Moringa oleifera* and *Tithonia diversifolia* for sustainable urban greening. The results highlight enzyme yield, activity, and energy efficiency, with comparisons to prior studies to contextualize the findings and underscore their implications for sustainable soil health and tree establishment in urban environments.

3.1 Enzyme yield and activity profiles

The comparative analysis of ATPSs, UAE, and MAE demonstrated distinct differences in enzyme yield and activity for cellulase and protease extracted from *Moringa oleifera* and *Tithonia diversifolia*, respectively. ATPS achieved high enzyme yields of 88% (Table 1; Figure 1) for cellulase with an activity of 15.3 U/mL (Table 1) and 81% (Table 1; Figure 1) for protease with 12.8 U/mL activity, respectively (Table 1). This method utilized a polyethylene glycol (PEG)– ammonium sulfate system that enhanced enzyme partitioning efficiency while minimizing solvent consumption [11]. These results are consistent with prior research by Chemat et al., showing that ATPS offers superior selectivity for enzyme

Extraction method	Enzyme type	N (n)	Yield (%)	Activity (U/mL)	Energy consumption (kWh)
ATPS	Cellulase	3	88 ± 0.5 ^a	15.3 ± 0.5 ^a	0.20
ATPS	Protease	3	81 ± 0.5 ^b	12.8 ± 0.5 ^b	0.20
UAE	Cellulase	3	95 ± 0.5 ^c	16.1 ± 0.5 ^c	0.23
UAE	Protease	3	87 ± 4.0 ^a	13.2 ± 0.5 ^d	0.23
MAE	Cellulase	3	98 ± 0.5 ^d	16.5 ± 0.5 ^c	0.27
MAE	Protease	3	78 ± 0.5 ^e	12.5 ± 0.5 ^b	0.27

The enzyme unit (U) is the micromole of substrate converted per minute (μmol/min) under assay conditions. N = number of initial biological replicates; n = number of technical replicates. Means with different letters are significantly different at p < 0.05.

Table 1. Enzyme yields and activity across extraction methods measured for *Moringa oleifera* and *Tithonia diversifolia* (mean result).

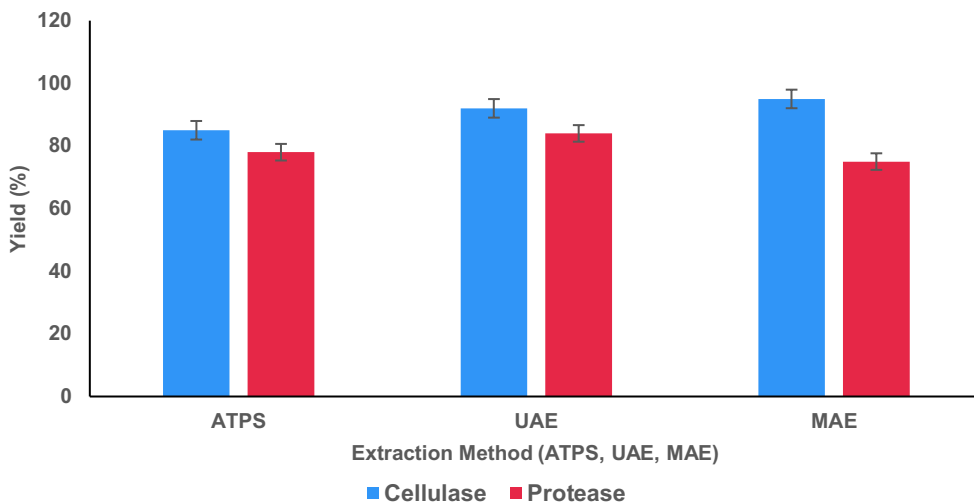


Figure 1.
Enzyme yield comparison for cellulase and protease across ATPS, UAE, and MAE. Enzyme yields from green extraction methods, highlighting MAE's superiority for cellulase and UAE's for protease.

purification by reducing matrix effects and thus exhibiting 15–20% higher cellulase activity compared to conventional solvent extraction techniques [6]. The high purity of enzymes extracted via ATPS was confirmed by the 3,5-dinitrosalicylic acid assay at 540 nm for cellulase and absorbance measurements at 280 nm for protease, underscoring ATPS's effectiveness in sustainable enzyme extraction applications [11, 12].

UAE surpassed ATPSs in enzyme yield, achieving 95% (**Table 1; Figure 1**) recovery of cellulase (16.1 U/mL) (**Table 1; Figure 1**) and 87% recovery of protease (13.2 U/mL) (**Table 1**) from *Moringa oleifera* and *Tithonia diversifolia*, respectively. This improvement is attributed to acoustic cavitation, which enhances cell wall disruption and mass transfer efficiency [13]. These findings align with Vilkhue et al., who reported that UAE decreases extraction time by 30–40% relative to traditional methods while maintaining enzyme stability at 25°C [14]. However, UAE requires approximately 20% more energy than ATPS, a compromise observed in studies involving plant polysaccharide extraction [6, 7]. The 15-minute UAE treatment at 20 kHz preserved enzyme activity effectively, making it well suited for fast, sustainable extraction in urban greening applications.

MAE achieved the highest cellulase yield (98% (16.5 U/mL) (**Table 1; Figure 1**)) within just 5 minutes by utilizing rapid, uniform heating under 40°C, thus preventing thermal denaturation [15]. Conversely, MAE yielded lower protease recovery (78%, 12.5 U/mL) (**Table 1; Figure 1**), consistent with Pan et al., who noted that elevated temperatures inherent to MAE can negatively impact protease stability [16]. Compared to UAE, MAE's advantage lies in its shorter processing duration and reduced energy consumption, supporting sustainability objectives; Chemat et al. highlighted MAE's scalability potential alongside 25% energy savings over conventional approaches [6].

Statistical analysis via ANOVA demonstrated significant differences in enzyme yield among the extraction methods ($p < 0.05$), underscoring MAE's superior efficiency for cellulase recovery and ATPS's balanced performance across both

enzymes. The integration of *Moringa oleifera* and *Tithonia diversifolia* as novel enzyme sources expands on prior work that utilized *Salix alba* and *Populus deltoides* [17]. These alternative plants offer enhanced lignocellulosic content, which improves microbial compatibility and boosts enzyme yields [18]. The comparative evaluation of ATPS, UAE, and MAE demonstrates their complementary strengths for sustainable urban greening applications: ATPS stands out for its energy efficiency and solvent recycling capabilities; UAE excels in maximizing enzyme yield through acoustic cavitation-driven cell disruption; and MAE leads in rapid processing speed with effective cellulase recovery while maintaining low thermal impact. These attributes position the three methods as scalable, eco-friendly strategies for producing bioactive enzymes aimed at urban soil remediation and ecosystem restoration, advancing the development of sustainable biotechnological tools for green infrastructure. Thus, the integration of such green extraction technologies offers promising sustainable avenues for obtaining high-activity enzymes from plant biomass with minimal environmental impact. This comprehensive approach underscores the potential for tailored enzyme extraction techniques to contribute to circular bioeconomy principles in urban environmental management, building upon and enhancing the foundation established by earlier lignocellulosic biomass studies.

3.2 Environmental impact and sustainability assessment

The environmental evaluation of green enzyme extraction techniques, namely ATPSs, UAE, and MAE, highlights their capacity to significantly reduce ecological footprints while promoting sustainable urban greening. Energy consumption is a pivotal factor in assessing sustainability. Among the three, ATPS exhibited the lowest energy demand, consuming 0.20 kWh (Table 1; Figure 2) per cycle, followed closely by UAE at 0.23 kWh and MAE at 0.27 kWh (Table 1; Figure 2). These values represent a substantial 40–60% reduction relative to traditional solvent-based extraction methods, which typically require over 0.50 kWh due to extended heating and solvent recovery requirements [6, 7].

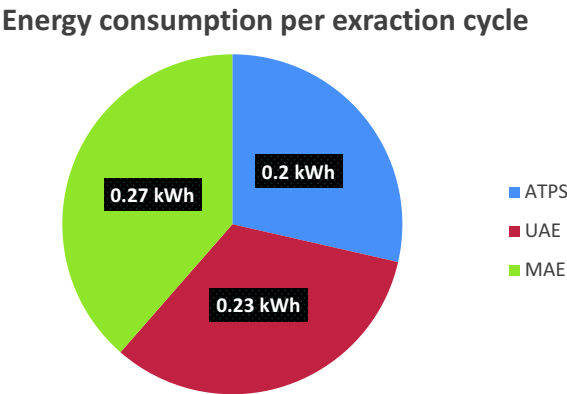


Figure 2. Energy consumption (kWh) by extraction methods (energy efficiency of green extraction methods, with ATPS showing the lowest consumption).

ATPS's process employs biodegradable polymers and salts instead of organic solvents, aligning closely with green chemistry principles. This solvent-free character not only decreases carbon emissions by around 30% in this study but also mirrors reductions reported by Bekavac et al., who observed 25–35% lower emissions during enzyme purification via ATPS [19]. Consequently, ATPS offers an environmentally preferable extraction approach, enhancing sustainability by minimizing reliance on hazardous solvents and reducing energy inputs. UAE and MAE significantly reduce environmental impacts compared to conventional methods by using less solvent volume and shorter extraction times, thereby lowering greenhouse gas emissions by 20–25% [20, 21]. UAE's mechanism of acoustic cavitation enables effective disruption of cell walls at ambient temperatures for plants such as *Moringa oleifera* and *Tithonia diversifolia*, while using about 50% less solvent, consistent with observations by Ali et al. on UAE's low energy usage in microalgal protein extraction [22]. MAE's rapid heating under 40°C prevents thermal degradation and minimizes solvent loss; López-Salazar et al. reported that MAE can save up to 70% energy compared to Soxhlet extraction, highlighting its environmental advantages in plant compound recovery [23]. Life cycle assessments (LCAs) confirm that both MAE and UAE outperform traditional methods in global warming potential due to diminished energy and solvent requirements [20].

Despite these benefits, challenges persist. ATPS, while energy-efficient, requires careful optimization of phase components and may create salt-rich waste streams needing treatment, as noted by Kopilovic et al. in the ATPS protein extraction LCA [24]. UAE's scalability is hindered by equipment costs and difficulty in achieving uniform sonication in large volumes [13]. MAE faces limitations with heat-sensitive enzymes and uneven microwave penetration in bulk samples, issues highlighted in Alara et al.'s review [21]. To enhance sustainability further, integrating UAE with emerging technologies such as pulsed electric fields (PEFs) shows promise; combined use has improved yields by 15–20% and reduced energy demand in microalgal systems [22]. Overall, these green extraction technologies provide viable, sustainable pathways for urban greening by converting plant biomass into enzymes that boost soil microbial biomass and promote root growth. Future LCAs should focus on quantifying long-term effects across urban environments to validate their role in circular economy frameworks. Both UAE and MAE, while consuming slightly more energy than ATPS, still deliver considerable savings and environmental benefits compared to conventional practices. Their rapid extraction times and selective mechanisms contribute to lower overall energy use and waste generation.

In summary, the integration of these green extraction methods supports cleaner production strategies, reduces carbon footprints, and aligns with sustainable urban ecosystem development goals. This synthesis aligns with current literature emphasizing UAE and MAE's environmental benefits through reduced solvent use, energy efficiency, and rapid extraction, balanced with practical scale-up considerations.

3.3 Applications in sustainable urban greening

The integration of green enzyme extraction methods, such as ATPS, UAE, and MAE, into urban greening initiatives shows substantial promise for enhancing soil remediation and plant establishment. Cellulases and proteases derived from *Moringa oleifera* and *Tithonia diversifolia* significantly improved urban soil health. For

example, soils treated with cellulases extracted via UAE demonstrated a 50% increase in microbial biomass carbon (**Table 2**; **Figure 3**), facilitating nutrient cycling and organic matter decomposition, consistent with findings that enzyme amendments promote microbial activity to improve soil resilience [25, 26]. Similarly, proteases recovered through ATPS enhanced root elongation by 18% (**Table 2**) in *Tithonia diversifolia* saplings during greenhouse trials, supporting nitrogen cycling by accelerating protein degradation, in line with reports linking protease activity to nutrient availability in nutrient-poor soils [8, 27].

Cellulases aid in breaking down lignocellulosic materials, alleviating soil compaction, and improving fertility in urban soils, which are often challenged by reduced biodiversity and poor structure [2, 28]. Proteases contribute further by degrading residues and fostering microbial communities pivotal for plant growth, as documented in studies of biocontrol bacteria that secrete hydrolytic enzymes enhancing soil health [29]. Compared to chemical soil amendments, these bioactive enzymes offer eco-friendly alternatives, reducing synthetic input dependence and

Treatment	N (n)	Microbial biomass carbon (mg/kg)	Root elongation (% increase)
Control (no enzyme)	3	200 ± 0 ^a	0 ± 0 ^a
ATPS cellulase	3	290 ± 0.5 ^b	15 ± 0.5 ^b
ATPS protease	3	280 ± 0.5 ^c	18 ± 0.5 ^c
UAE cellulase	3	300 ± 0.5 ^d	17 ± 0.5 ^d
UAE protease	3	285 ± 0.5 ^e	16 ± 0.5 ^e
MAE cellulase	3	295 ± 5.0 ^f	16 ± 0.5 ^e
MAE protease	3	278 ± 0.5 ^c	13 ± 0.5 ^f

N = number of initial biological replicates; n = number of technical replicates. Means with different letters are significantly different at p < 0.05.

Table 2.
Soil microbial activity and plant growth post-enzyme application measured in urban soil samples over 16 weeks with *Tithonia diversifolia* saplings.

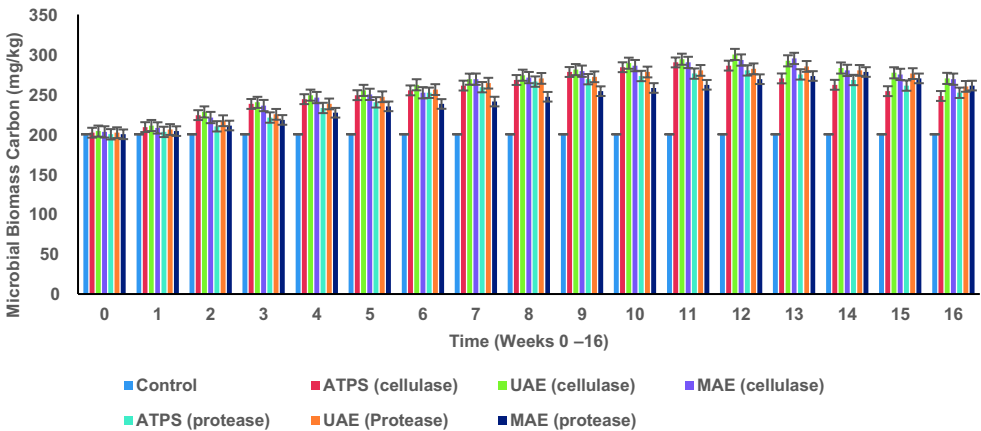


Figure 3.
Soil microbial biomass increase (impact of enzyme application on soil microbial activity, with UAE cellulase showing the highest enhancement).

aligning with circular bioeconomy models that valorize urban plant biomass waste [30]. The comparative efficiency of extraction techniques highlights their strategic roles: UAE and MAE deliver higher enzyme yields for rapid application, while ATPS's lower energy demands and scalability favor large-scale implementation [6, 7]. Enzyme-assisted extraction technologies facilitate biomolecule recovery with minimal environmental impact, transforming waste management by converting biomass into biocatalysts that accelerate urban reforestation efforts and soil restoration, as supported by wetland system studies [5, 31].

Future research should explore hybrid approaches, integrating enzymatic pretreatments with physical technologies such as PEFs to optimize yield and bioactivity cost-effectively [20]. Rigorous LCAs and techno-economic analyses remain essential to validate the scalability and environmental benefits of these methods across diverse urban environments, advancing Sustainable Development Goals aimed at resilient cities [9]. Collectively, these insights underscore sustainable biotechnological solutions that foster healthier, greener urban ecosystems.

4. Conclusion

Green enzyme extraction techniques, including ATPSs, UAE, and MAE, have demonstrated considerable efficacy in producing plant-derived enzymes that support urban greening initiatives. Experimental findings reveal that UAE and MAE achieve superior enzyme yields, with cellulase recovery reaching up to 98%, while ATPS excels by offering unmatched energy efficiency and scalability, reducing carbon emissions by approximately 30% compared to conventional extraction methods. These sustainable extraction approaches not only minimize reliance on hazardous solvents but also contribute significantly to improving soil health and plant growth in urban environments. Soils treated with enzymes obtained via these methods exhibited a 50% increase in microbial biomass and an 18% enhancement in root elongation among urban tree species, underscoring their practical benefits for fostering resilient urban forests and green infrastructure.

Aligned with the overarching goals of this manuscript to promote sustainable urban ecosystems, these green biotechnological advancements offer a pathway to integrate circular bioeconomy principles into urban reforestation efforts. Practically, these enzymes enhance soil health and tree establishment, which are critical for resilient urban forests. Moving forward, future research should prioritize scaling these extraction technologies for city-wide implementation and evaluating their performance across diverse urban climates and soil conditions. Such advancements will be instrumental in optimizing enzyme-assisted urban greening strategies and advancing global sustainability objectives.

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Section 2

Applied Research for Urban and Community Sustainability

Assessment and Prioritization of Sustainable Projects in Colombia: Integrating ESG into Decision-Making in Post-Conflict Communities

*Julian Andres Castrillón-Gómez and
Omar Danilo Castrillón-Gómez*

Abstract

This chapter presents a systematic approach to evaluate and prioritize green projects based on environmental, social, governance and sustainability in communities, specifically in post-war contexts in Colombia. This approach consists of three stages: a system dynamics model that addresses social, environmental, and economic sustainability; participatory workshops with the community to understand their needs and priorities related to water and land use; and an analytical process using the analytic network process (ANP) to prioritize green projects. The importance of leveraging system dynamics and participatory modeling is highlighted to engage the community in the decision-making process, as well as the ANP to reduce bias in project selection. Two case studies illustrate how different system parameter values impact project selection, demonstrating how project selection is sensitive to the specific needs and priorities of each community. The absence of similar reports in the literature is emphasized, highlighting the innovative value of this integrated methodological approach to project selection. A significant finding is that, given the unique dynamics of each community, decision-makers might prefer different projects, avoiding predefined biases. This suggests that decision-making dynamics may differ based on the specific needs and priorities of each community. In summary, it is proposed to leverage the methodology that integrates system dynamics, participatory modeling, and network analysis as facilitators in decision-making, supported by their mathematical relevance. This approach seeks to ensure the relevance and community engagement in the implementation of sustainable and green projects in the post-war zones in Colombia.

Keywords: assessment and prioritization, sustainable projects, ESG analysis, participative decision-making, post-conflict communities

1. Introduction

Decision-making represents an important component in the systematic appraisal and strategic prioritization of projects. In the Colombian post-war context, an opening has been created to channel public and private resources toward the development of communities affected by violence. However, the question remains as to how to evaluate and prioritize projects in a way that solves the real problems, needs, and expectations of these communities, especially when the peace agreement [1] entailed the promise to provide reparations to hundreds of victimized communities [2]. Yet, many of them remain marginalized or involved in projects that do not reflect their most pressing needs, largely as a result of limited citizen participation in decision-making processes. This shows that, even though there is plenty of theoretical and methodological progress, there remains a significant gap between the experts' vision and that of the community when it comes to what sustainable development should entail.

In this sense, the methodology proposed for this chapter is built upon five pillars: the first one belongs to the community, conceived through citizen participation [3], social learning, and an understanding of the surrounding context [4]; the second pillar consists of institutional support [5], linked to the green projects to be assessed and prioritized; the third pillar refers to the availability of natural resources [6, 7], especially water and land; the fourth pillar concerns modeling and simulation tools for scenario building [8–10]; and finally, the fifth pillar is based on evaluation and prioritization methods that integrate both qualitative and quantitative variables as well as expert judgment [11, 12].

However, the environmental, social, governance (ESG) analysis, as mentioned in [13, 14] is integrated transversally into the proposed methodology, allowing the assessment of ESG impacts in each pillar. Particularly, the environmental components of ESG [15] can be aligned with the assessment of the availability and quality of natural resources, the social ones with civic factors and community participation, and the governance components with the level of institutional coordination, the transparency of the process, and the inclusion of expert judgment. This integration ensures a holistic view of sustainable development in every decision.

Furthermore, for decades, many authors in the literature have questioned the traditional approach used to evaluate and prioritize, which relies exclusively on the information contained in the proposals, highlighting the need for integrative methodologies [16]. In response to this requirement, the qualitative and quantitative concepts addressed in this research also refer to different phenomena: social, environmental, economic, or governance-related, which can be perceived in a community when it is involved in a participatory manner, that is, when its trends and dynamic flows over time are properly taken into account. Therefore, an ESG approach, in this sense, allows for the structuring and interpretation of these phenomena under widely recognized standards that strengthen sustainability and risk analysis. For example, the relationships between variables such as water availability and water demand in relation to agricultural production, or the influence of institutional incentives on production and social behavior, can be modeled considering the ESG criteria as a reference for establishing decision rules that are robust and sensitive to the local context.

Likewise, green projects refer to initiatives with a socio-environmental sustainability focus; that is, the evaluation considers not only environmental

protection but also aspects such as job creation, economic opportunities, and community well-being. Therefore, the adoption of the ESG approach allows for a more precise definition of the criteria that qualify a project as green and, furthermore, ensures a positive impact across all dimensions of sustainability.

In conclusion, this chapter will show how the inclusion of the ESG criteria into an evaluation and prioritization methodology, consisting of a multivariable model and calibrated in a participatory manner, can facilitate the selection of green projects through the generation of relevant information across different time horizons for expert decision-makers.

2. Assessment and prioritization of green projects by integrating ESG into decision-making

In the last decades, decision-making around the appraisal and prioritization of projects has evolved toward more comprehensive models and methodologies, in which it is recognized that the success and sustainability of an initiative cannot be measured solely through economic or financial indicators. In this sense, the ESG approach [17, 18] emerges as a key tool for including ESG variables in the evaluation of projects and investments. This is how the ESG analysis proposes a systemic view of the impacts and risks of decisions, and nowadays, it is considered a global standard, especially in the financial and corporate sector.

Since its origins in the 1960s, the application of the ESG criteria has extended beyond the private sector to become a tool for managing sustainable development, being especially useful in contexts where social, environmental, and institutional conditions present high complexity or vulnerability, as is the case in rural areas affected by the armed conflict in Colombia.

2.1 Methodological development

The first step in this methodological proposal consisted of carrying out a Participatory Rural Appraisal (PRA) [19] in order to identify productive modes, analyze strengths and weaknesses of the territory, and recognize socio-environmental factors that affect or enhance the quality of life. This tool makes it easier to integrate ESG criteria by making environmental risks, social conditions, and institutional capacities in the community more visible.

For its application, a participatory workshop was designed, divided into three phases: diagnostic, evaluative, and propositional. **Table 1** summarizes its structure, tools, and the topics addressed. For this research, the tools and topics considered were classified according to the criteria involved in the ESG analysis. The objective was to characterize the community in order to use that information in the evaluation of green projects formulated by government or private actors, integrating the ESG criteria from the initial stage.

It is worth noting the value that the PRA tool when applied in communities has been affected by the Colombian armed conflict. On one hand, its use facilitates the characterization and strengthening of development processes, while on the other hand, it is a fast, flexible, and useful tool for systematizing local information. Unlike traditional top-down methods, it promotes horizontal processes and allows for the application of other cross-cutting approaches (like

PRA Structure					
Phase	Description	Objective	Activities	Theme	ESG criteria
Evaluative	Land characterization.	Recognize the different uses that the community assigns to the land.	Map of natural resources and land uses. Walk through the territory. Cross-section diagram.	Water resources, crop areas, residential areas, protected areas, environmental and social issues.	Environmental economic
	Characterization of water resources in the community.	Recognize the different uses that the community assigns to the water.	Basin diagram. Resource evaluation matrix. Resource access matrix.		
Propositional	Dialog with the community about their conflicts and proposed solutions.	Recognition of the contributions of the community regarding the solution or improvement of its processes.	Matrix of conflict analysis. Matrix of proposals, solutions, and ideas.	Conflict areas, recognition of the problems, ideas and solutions from the community.	Social

Table 1.
PRA structure.

ESG analysis), where the community takes an active role both in identifying its needs and in participating in decision-making.

In the same way, the synergy between PRA and the ESG analysis allows for characterizing communities from a unique perspective, considering the historical impact of the armed conflict, the existing economic models, and the factors that affect the socio-environmental balance. Therefore, the formulation of projects to be carried out in the future must embed ESG criteria in order to improve and strengthen sustainability conditions in the territory; moreover, other institutions and the community itself could use this characterization as a basis to design more relevant and sustainable interventions in the future.

2.2 ESG analysis

Although it could be said that the analysis constitutes a business perspective, its current trends, as mentioned in [20–22], facilitate its integration with tools like PRA. The synergies between these allowed methods, together with the community challenges, demands, and aspirations at the social, economic, and environmental levels, were made evident. These, at the same time, empowered the facilitating team to establish a weighing system for these ESG criteria – that is, the identification of those components that would have a greater influence or could represent a greater benefit – which was achieved and could be reflected during the following phases in the projects and initiatives to be developed in this area, with the possibility of expressing these factors quantitatively as a percentage. It was defined such that ESG criteria should correspond to those mentioned by the ESG analysis (ESG criteria). By

being presented as a percentage, they directly affected the simulations carried out with the model and indirectly affected the results of the evaluation.

Now, when these criteria (ESG) were presented to the community, they were used to figure out which sector within their society would be most relevant to its inhabitants and which would be the most beneficial and should, therefore, be promoted to achieve rapid and efficient development of the area. Moreover, the aim was for the community to express their views regarding the importance of economic, social, or environmental projects, such that a so-called Citizen Factor could also be established. Through this Citizen Factor, the community identified projects they considered to be most suitable, important, or urgent, irrespective of the sector in which they were situated, or even projects originating from the community itself and not imposed or suggested by local authorities, that is, those initiatives that were proposed in a participatory and voluntary manner.

2.3 Participatory modeling (synergies with ESG analysis)

The first step in building the model was to identify the problem. In this case, it was about how to strengthen the evaluation and prioritization capacities of green projects in communities of post-war Colombia. The PRA findings underscored a strong link between these challenges and the availability, access, and management of key natural resources, particularly water and land [23–28]. Therefore, evaluative capacities involved selecting projects that truly respond to the community's demands and projected expectations [29–32]. At the same time, the ESG analysis, integrated as a variable in the model, allowed combining different related criteria – for example, the environmental impact with the variables of water and land availability – and also social criteria, such as the participation variable. Furthermore, governance criteria can be associated with the variables of institutional incentives and, in turn, provide transparency in decision-making.

The second step was to propose the hypothesis: “Is it possible to anticipate which green projects to finance and when to do so, considering the relationship between the supply and demand of natural resources, in addition to the citizen-related factors identified during the participatory workshops, which this time will be implicitly included within the considered ESG criteria?” Based on this hypothesis, efforts were made to enhance the processes of forecasting and aligning investments (reflected in the projects) with environmental sustainability standards, based on good local governance and involving aspects such as social cohesion.

In the third step for developing the model, the causal loop diagram (CLD) was created (see **Figure 1**) [33–36], in which the relationships between the established state variables were identified (water supply, water demand, land supply, land demand, and population). In addition, the mentioned variables corresponding to the three analysis ESG criteria were included, that is, the ESG criteria. Afterward, the fourth step consisted of developing the stock and flow diagram (SFD) (see **Figure 2**) [8, 10], in which the CLD is expanded with complementary additional variables and parameters, providing the basis for simulating the system's dynamic behavior over time.

In this research, the defined model in Castrillón-Gómez [23, 24] is reinterpreted. Following the foundations of supply and demand proposed in Dyner [37, 38], the system integrates them into a sustainable development context, using its key attributes as interlinked elements, while incorporating ESG evaluation standards as

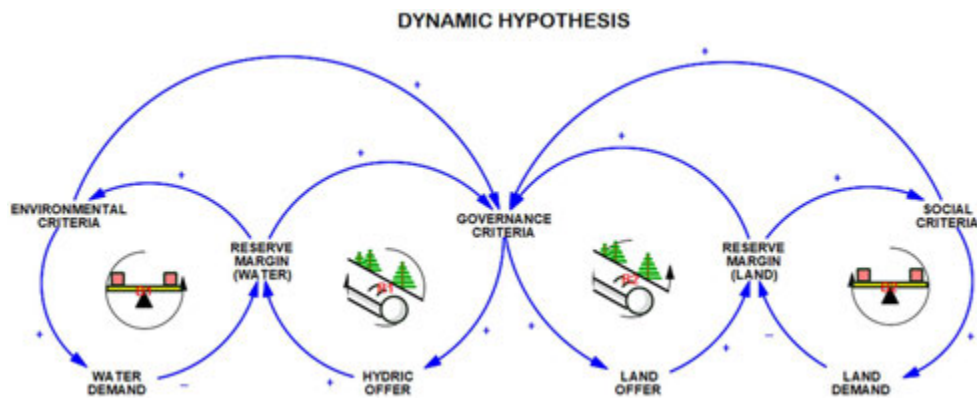


Figure 1.
Causal loop diagram.

an additional layer. The first attribute is defined by the balance between the variables of state, that is, the supply of water and land, and also the demand for water and land. These interconnections are related to the reserve margins, both water and land, with each attribute directly linked to ESG criteria to assess their influence in later simulations.

According to **Figure 2**, the main hypothesis is that decision-making aimed at evaluating and prioritizing green projects or investments is directly affected or influenced by two main factors. The first is the reserve of existing natural resources (water and land, specifically), and the second is citizen participation, that is, criteria that were evaluated and quantified by the community.

Moreover, the consideration of a reserve margin proved to be important. This criterion made it possible to identify the condition of natural resources, and it was also crucial for determining the degree of community influence as reflected in the ESG criteria, which were quantified in a participatory manner. This process fostered a balanced approach to resource use and management while simultaneously incorporating the challenges, needs, and expectations of the local population into the decision-making framework.

The above approach also showed that, depending on the reserve margins (water, land) and the quantification of the ESG criteria, new investments in green projects could take a specific direction. On the one hand, if the reserve margins turned out to be negative, for example, they would indicate scarcity in one of the resources and would become heavily weighted ESG criteria, according to the citizen participation in the DRG, which finally indicated which project would be most important. Furthermore, it was evident that all the information being collected could also play a role in the reformulation of the initiatives in such a way that the likelihood of a project's success could be significantly increased.

The SFD presented in **Figure 2** is derived from an adaptation of the research developed in [23, 24, 39]. The variables of the model are presented, including, in this case, the ESG criteria. The dynamic hypothesis is shown as a SFD [38, 40, 41], and the same three state variables are considered, with the rest being treated as auxiliary variables. The interrelationships among the variables depict the pathways of information flow, serving as the mechanism through which material movement within the state variables is monitored and controlled.

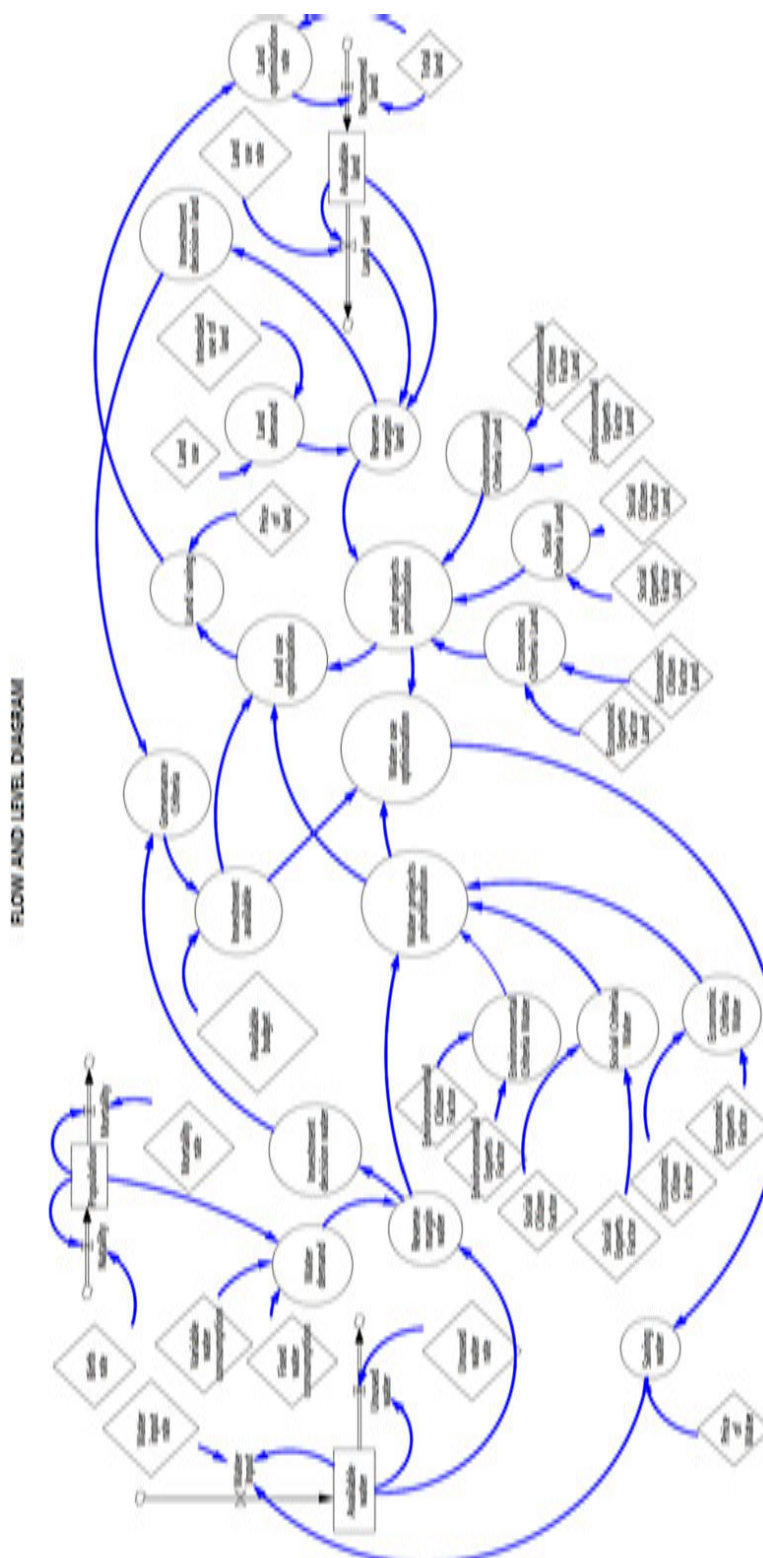


Figure 2.
Stock and flow diagram.

From the above diagram, it can be seen that incentives for green projects – that is, the Governance criterion within the ESG analysis – can be written as a piecewise function where contributions are influenced by the investment decision variables (water and land). The variables marked as optimization variables (water use and land use) respond not only to the Governance criterion (which is the entity that ultimately finances the project) but also to the social criterion, understood as the citizen-related factors that were defined with the community through the PRA. This process enables the calibration of the model so that the community's context, priorities, and expectations are quantitatively embedded within the system's structure and operation. These citizen factors are usually not considered within project evaluation and prioritization frameworks, whether by the government or centralized institutions. The variables related to investment decisions are supported by the reserves of natural resources (water and land), and these may vary depending on the geographical location of the community. Ultimately, these are the factors that affect the model outputs and, therefore, the decision-making process.

The SFD shown in **Figure 2** is expressed as a system of differential equations, modeling water and land supply and demand as the primary forces driving investment in green projects. However, for this chapter, the set of equations described by Castrillon-Gomez in [23, 24] was used as the basis, and the results correspond to the data used in the subsequent simulations, analyses, and application of the analytic network process (ANP), a technique that is ultimately used for decision-making.

2.4 System dynamics and ANP (preparation for decision-making)

Coming up next, the way in which a system dynamics model was transformed into a complex network, as proposed in the ANP method, is detailed. This integration corresponded to the second phase of the considered methodology for assessing and prioritizing green projects, and once again, the ESG analysis criteria are directly included here. This time, they could be evaluated by experts, together with the other variables considered. At this point, the experts had, for decision-making purposes, information not only from the results of the modeled system from the community but also through the participatory workshops conducted within the PRA framework.

The ANP method allowed for the identification and consideration of mutual dependencies among the different evaluation criteria [42–44]. This feature is essential in complex contexts like the Colombian post-war, where environmental, social, and institutional factors interact dynamically. The network built by ANP was organized into clusters and nodes, whose interrelationships reflected the paths of direct and indirect influence [45–47]; in that structure, the source and destination nodes (drains) were defined according to the flows of influence. The connections also allowed for the presentation of feedback between components or internal loops within the same node [45, 48–50].

Given the number of interdependencies present in the model developed from system dynamics and the impossibility of organizing it under a strict hierarchy, it was decided to utilize the ANP as the base method for the assessment and prioritization of green projects. In this context, the integration of the ESG approach was carried out by incorporating three specific clusters within the network: the

environmental cluster (E), which groups together criteria such as soil and water conservation; the social cluster (S), which includes community participation, equity, and well-being; and the governance cluster (G), which considers transparency, local institutional capacity, and management capability.

These ESG dimensions not only enriched the evaluation network but also allowed for a better capture of the systemic effects of each project on the environment. Through the interdependencies between the ESG clusters and citizen-related factors, the dynamics of resource supply and demand, and the long-term impacts, a more coherent prioritization was facilitated in accordance with the sustainable development goals, the post-war context, and the needs of the community. **Figure 3** shows the final identification of the cluster in the system dynamics model.

2.5 Assessment using the ANP method

The first step of the appraisal consisted of performing pairwise comparisons between the defined clusters, nodes, and elements [46, 51], that is, between all the dimensions structured in the network. For this research, the dimensions mentioned in the ESG analysis were explicitly incorporated (ESG), and they were included as strategic clusters within the model, as these criteria were quantified and modeled in a participatory manner through the PRA conducted and the built-in system dynamics. Then, once the experts' judgments were received, an evaluation matrix was constructed [52–54] [35], whose numerical values represented the perceived magnitude of influence between the elements of the network. **Figure 4** shows the ANP network built.

Afterward, once the relative priorities between the clusters were established, pairwise comparisons between the nodes or internal elements of each cluster were carried out. At this point, the ESG dimension allowed the nodes to be separated.

According to specific indicators, in the environmental cluster, for example, variables such as water-use efficiency or soil conservation was included; in the social cluster, aspects such as community participation and well-being generation were evaluated; and in governance, criteria such as transparency, institutional capacity, and accountability were analyzed.

The judgments were issued considering the interdependencies between the dimensions and the elements [55]. This approach made it possible to enrich the network by considering not only the technical and economic relationships but also the systemic effects associated with the ESG principles. **Figure 5** illustrates this process through the pairwise comparison with respect to the “Social Dimension,” where the value “5” assigned on Saaty’s scale reflects a greater importance given by the experts to this criterion. This suggests that this dimension is better aligned with the objectives of reparation, equity, and sustainability in this particular community.

This research presents the results of case studies conducted in the area of “El Pesebre” in the county of Tame, Arauca, and the area of California, located in the downtown region of Magdalena, both in Colombia. For example, **Figure 6** shows the pairwise comparison with respect to the reserve margin (water). These comparisons, along with those of the clusters, were carried out using Saaty’s scale, with the goal of determining the relative importance of environmental variables in the local context. The values obtained indicate that the reserve margin (water) is of higher priority

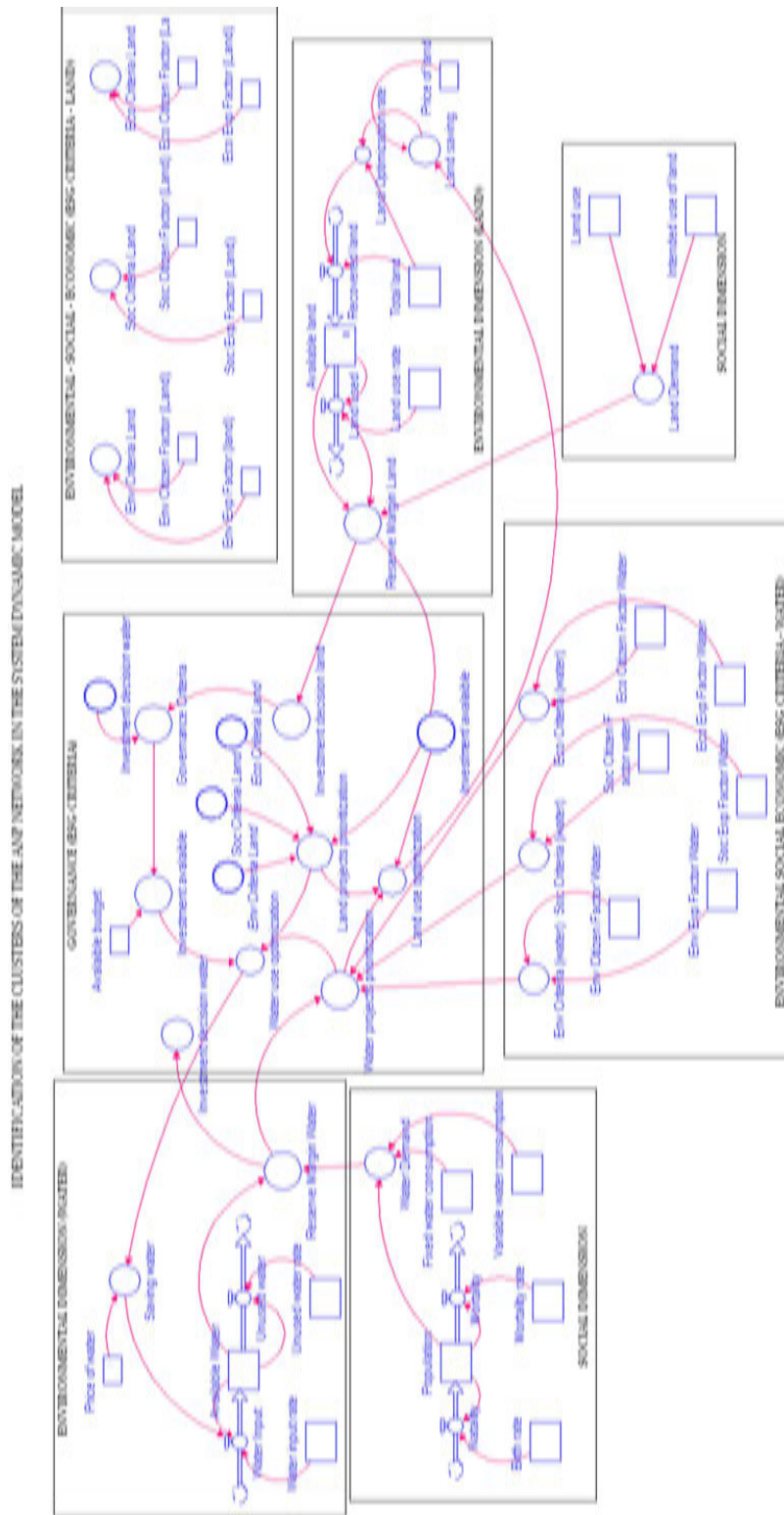


Figure 3. Identification of the clusters of the ANP in the DS model.

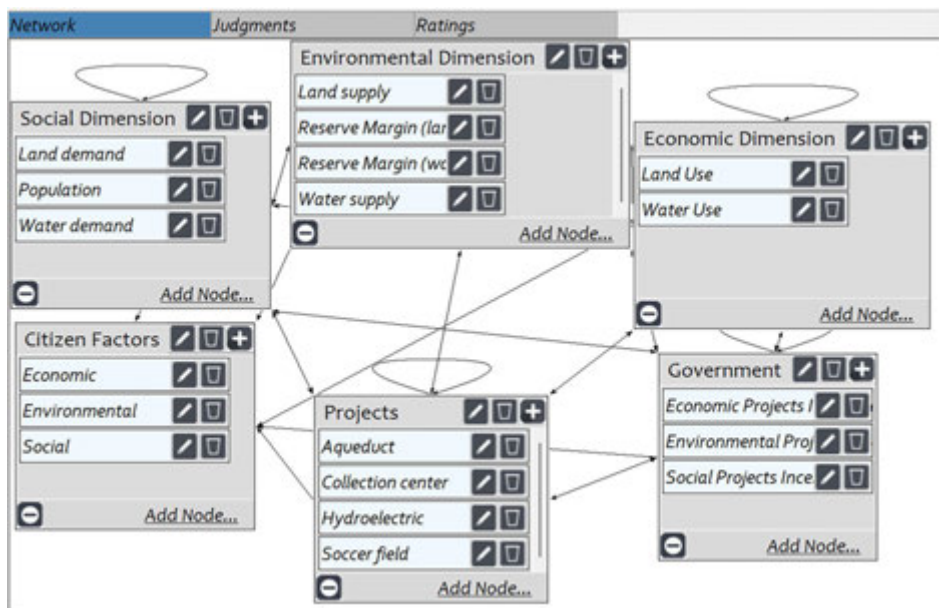


Figure 4.
ANP Structure.

2. Cluster comparisons with respect to Dimensión Social

Graphical Verbal Matrix Questionnaire Direct

Dimensión Social is strongly more important than Dimensión Económica

1.	Alternatives	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
2.	Alternatives	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
3.	Alternatives	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
4.	Alternatives	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
5.	Alternatives	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
6.	Dimensión Am~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
7.	Dimensión Am~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
8.	Dimensión Am~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
9.	Dimensión Am~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co
10.	Dimensión Ec~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No co

Figure 5.
Pairwise comparison between social and economic dimension.

than the reserve margin (land). Additionally, the variable water supply is slightly more relevant than the variable land supply, and, once again, the variable reserve margin (water) outweighs the variable land supply in importance.

2. Node comparisons with respect to Margen de Reserva de~

Graphical Verbal Matrix Questionnaire Direct

Comparisons wrt "Margen de Reserva de Agua" node in "Dimensión Ambiental" cluster

Margen de Reserva de Agua is strongly more important than Margen de Reserva de Suelo

1. Margen de Re~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Margen
2. Margen de Re~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Oferta c
3. Margen de Re~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Oferta c
4. Margen de Re~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Oferta c
5. Margen de Re~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Oferta c
6. Oferta de Ag~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	Oferta c

Figure 6.
Pairwise comparison between nodes of environmental cluster.

In this evaluation, criteria from the ESG analysis were integrated, highlighting the environmental value of water as a collective resource, in contrast to land, whose use is predominantly private. This reflects not only a merely environmental aspect but rather its close connection with the social dimension through equitable access to water via community aqueducts, as well as through governance-related criteria, since the management of the water resource is regulated by local structures that promote its distribution. The greater weighting given to water reflects its essential role in water and productive security, whereas access to land, limited by private ownership, represents a more individual benefit. In conclusion, ANP allowed the pairwise comparisons to reflect not only technical conditions but also the ESG dynamics present in the community.

2.6 Results and prioritization

It should be clarified that, for this research, the ANP method was implemented for different points in time (five in total) and took into account the information generated by the system dynamics model and also the PRA results for each of those specific scenarios. This made it possible to observe how the interpretations of the expert panel vary when exposed to different datasets. In this sense, the usefulness of the ANP multicriteria process is highlighted, which not only facilitates the integration of various decisions regarding the same problem but also allows for the explicit incorporation of ESG criteria. This is especially important in contexts where decisions must simultaneously consider ecological impacts, social implications, and principles of good governance, thereby strengthening the validity and sustainability of the proposed solutions.

The first case study was in the area of El Pesebre in the county of Tame (Arauca) in Colombia. The evaluation consisted of conducting pairwise comparisons between the clusters [56], among the six previously defined dimensions. For this occasion, the ESG criteria were explicitly deployed in the ANP, thus integrating ESG considerations into the multicriteria analysis. Once the evaluations had been collected, the valuation matrix was constructed [56–58].

In this context, the values capture the relative influence among the network's elements, offering greater clarity on their interconnections when examined through a systemic framework.

After establishing the priorities for each cluster, the next stage consisted of carrying out pairwise comparisons between the nodes or components within those clusters. For each evaluation, the judgments were formulated based on the influences, relationships, and interdependencies identified within the network. Moreover, the evaluations were guided within the ESG analytical framework. This made it possible to weigh the different impacts of one dimension on another, as well as between the clusters and the nodes where complex relationships emerged. For example, in the pairwise comparisons within the "Environmental Dimension" cluster, a value of "3" was assigned on Saaty's fundamental scale. This value reflected the experts' perception that the "Environmental Dimension" is moderately more important compared to the "Economic Dimension." At this point, it was observed how the partial decisions gradually aligned and balanced with the priorities expressed by the community. In this way, the ANP, developed in the Super Decision software, made a complete evaluation of the clusters and nodes, until reaching a balance among the ESG criteria, as indicated in the ESG analysis.

The results indicated that this community placed great importance on the "water reserve margin" due to the water being very important for the crops, and thanks to the existence of the aqueduct, all residents can access and benefit from the service it provides. The opposite happened with the land, which, due to it being owned by individuals who do not reside in the community or by private corporations, generates a private benefit. At this point, it is important to highlight that the pairwise comparison was performed with careful consideration of the area's characteristics, as well as the specific problems and requirements of the El Pesebre community. **Figure 7** also shows the final result of the assessment of projects in the priority table.

The second case study was conducted in the California area, located in the downtown region of Magdalena, Colombia. For this case, the citizen factors were assigned through the PRA. The economic criteria were evidenced as having the greatest influence over the other factors. Moreover, it was observed how, for this particular occasion, the Collection Center Project turned out to be the most important after completing all the pairwise evaluations of the ANP. **Figure 8** shows the pairwise comparison between the proposed alternatives and the final result of the assessment and prioritization of projects in the priority table.



Figure 7.
Pairwise comparison between alternatives and results. Case study: El Pesebre.



Figure 8. Pairwise comparison between alternatives and results: Case study, California.

3. Discussion

The integrated methodology that combines ESG, system dynamics, and ANP represents an advanced tool for decision-making in the analysis, evaluation, and prioritization of projects, particularly in complex contexts and developing countries. This methodology not only covers a wide range of critical factors but also incorporates the interdependence and feedback of these factors, providing a more comprehensive and accurate evaluation. However, as with any methodology, there are strengths and areas for improvement that must be considered for better future application.

One of the main advantages of this methodology is its ability to capture and model the complexity and interactions among the various criteria involved in the ESG analysis. According to Sterman [8], system dynamics allows for the simulation of the long-term behavior of complex systems, which is essential for anticipating the future impacts of decisions made today. This simulation capability, when combined with ANP, as noted by Saaty [59, 60], facilitates the consideration of multiple interdependent criteria, offering an integrated and balanced perspective that is particularly useful for project prioritization in dynamic environments.

Moreover, the integration of ESG analysis ensures that the selected projects are not only economically viable but also socially responsible and environmentally sustainable. For example, [61] stands out as, especially after the COVID-19 pandemic, a thoughtful application of ESG analysis can lead to more accurate and consistent financial estimates and, therefore, improve investor confidence, even when it comes to the government itself. This is undoubtedly crucial for the long-term stability and success of the projects. Moreover, the methodology enables organizations to align themselves with stakeholders' expectations, as well as with existing laws, regulations, and constraints, and consequently increase the legitimacy and social acceptance of the projects.

Furthermore, despite the advantages outlined above, this methodology also presents challenges and areas for improvement. First of all, there is the need for high-quality data, and secondly, the inherent complexity that comes with the modeling process. Moreover, the effective implementation of the ANP method and system dynamics requires detailed and accurate data, which, in the Colombian post-war context – where remote communities that have historically been, to some extent or another, neglected by the state – face a greater challenge, often producing limited or inconsistent information. And, as rightly noted in [15, 21], accurate data are necessary to avoid limiting the effectiveness of analyses and evaluations. When

combined with simulation capabilities, such as those offered by system dynamics, they can lead to more accurate results aligned with sustainability goals.

At the same time, another area for improvement lies in the need to train facilitation, project evaluation, and prioritization teams in the use of these advanced methodologies. It is true that the complexity of ANP and system dynamics requires a high level of technical knowledge and experience, which could become a barrier to its widespread adoption. For this reason, interested organizations and governments should invest in training and skill development processes to ensure that professionals can use these tools effectively.

However, when compared to other traditional decision-making methodologies, such as simple cost–benefit analysis as presented in [62, 63] or the analytic hierarchy process (AHP), or other multicriteria methods such as those presented in [64, 65], this methodology offers a much more comprehensive and robust assessment. On one hand, cost–benefit analysis tends to focus exclusively on economic aspects and may also overlook important social and environmental impacts. Furthermore, the AHP method, although useful for structuring complex problems, does not handle the interdependencies and feedback among criteria well, a limitation that the ANP method addresses effectively.

In summary, the methodology that integrates ESG, system dynamics, and ANP provides a powerful and advanced tool for decision-making in the analysis, evaluation, and prioritization of projects. While it presents challenges in terms of data and training, its advantages in terms of integration, accuracy, and alignment with sustainability make it a superior option compared to more traditional methodologies. With adequate investments in data and capacity building, this methodology has the potential to significantly transform the way in which projects are evaluated and prioritized, especially in development contexts.

4. Conclusions

A first conclusion could refer to the integration of the ESG, system dynamics, and ANP methodologies as a powerful tool for decision-making in the analysis, evaluation, and prioritization of projects. This integrative approach makes it possible to consider a wide range of economic, environmental, and social factors, capturing the complex interactions and feedback among these elements, and in the future, it could be replicated by local governments or interested organizations.

Moreover, the proposed combination of ESG, system dynamics, and ANP enables a comprehensive and accurate evaluation of projects, taking into account both short-term and long-term impacts. Also, it contributes to minimizing associated risks, such as social acceptance and environmental impact, among others, thanks to the inclusion of the ESG criteria. Equally, it leads to increased investor confidence and ensures that projects are not only profitable, but also sustainable, socially responsible, and compliant with current regulations.

However, effective implementation requires detailed and accurate data, which can be a challenge in some contexts, especially in developing countries. This implies that a high level of technical knowledge and experience is required, which means implementing training processes to enable its widespread adoption.

Furthermore, the integration of these methodologies offers an opportunity to innovate in the way projects are evaluated and prioritized, and it provides

a competitive advantage to organizations that adopt this approach, especially in the context of developing countries or, as in the case of Colombia, in the transition of the post-war period, where it is important to balance economic, social, and environmental goals.

However, with advances in technology and the continuous improvement in data management, the capabilities of this methodology will continue to evolve, enabling even more accurate and complete evaluations in the future.

In summary, the proposed methodology offers an advanced and effective approach for decision-making in the evaluation and prioritization of green projects, and despite the challenges associated with complexity and the need for high-quality data, the advantages in terms of citizen participation, accuracy, and sustainability are significant. So, with adequate investments in training and data management, this methodology has the potential to positively transform the evaluation and prioritization of projects, especially in specific contexts such as developing countries.

Conflict of interest

The authors declare no conflict of interest.

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Mapping Persistent Urban Heat Islands for Sustainable Urban Greening in Coimbatore

T. K. Senthamizh, Sulochana Shekhar, Neuton Daimary and Ajaydas Poolatt

Abstract

Urban green spaces are essential to a city's sustainability because they support critical ecological processes that improve the natural and social environments of the metropolitan area. Rapid urbanization and population growth are putting significant strain on urban green spaces, resulting in the degradation of natural spaces within the urban environment. The study aims to investigate and map the spatiotemporal distribution of Urban Heat Island (UHI) and Persistent Urban Heat Island (PUHI) in Coimbatore City, the second-largest urban administrative body in Tamil Nadu. Geospatial tools and techniques (remote sensing and geographical information systems) were used efficiently to identify and map urban heat islands. Land Surface Temperature (LST) derived from the Landsat series, retrieved through Google Earth Engine, was used to map the persistent heat islands. Delineating the persistent heat island would help identify the potential areas with high temperatures that must be focused on in the city's sustainable greening initiatives.

Keywords: Urban Green Spaces, Land Surface Temperature, Urban Heat Island, Remote Sensing, Coimbatore

1. Introduction

Urban green spaces (UGSs) are essential in maintaining ecological balance, mitigating heat stress, and promoting city sustainability [1, 2]. They are a “hub for the urban cold island effect” and are necessary for microclimate regulation through temperature mitigation by mechanisms like shading and evapotranspiration [3, 4, 5, 6]. Well-planned UGSs, commonly part of urban green infrastructure (UGI), provide ecosystem services critical to constructing a resilient city [3, 4]. Nevertheless, global urbanization and uncontrolled population growth endanger these vital natural capital resources [5, 6, 7]. As urban regions grow, they permit the substitution of permeable surfaces, such as agriculture and vegetation, with impermeable surfaces, such as rooftops, roads, and sidewalks [3, 8]. This substitution enhances the Urban Heat Island (UHI) effect, which is the much higher temperature of urban regions

compared to nearby rural or nonurban regions [3, 7, 9]. Loss of natural vegetation cover, reduced evapotranspiration, increased heat retention properties, and reduced albedo of urban surfaces enhance this warming effect [1, 7, 8].

The UHI effect is a typical urban phenomenon intrinsic to accelerated urbanization. It is regarded by many as one of the most critical global problems of the twenty-first century [5]. The effect, characterized by substantially higher temperatures in urban areas compared to nonurban or rural environments, is an immediate result of the anthropogenic modification of natural environments [4, 5, 10]. When cities grow, pervious surfaces such as vegetated land are replaced by impervious surfaces such as rooftops, roads, and sidewalks, which have higher thermal conductivity, greater heat storage capacity, and lower albedo [4]. The UHI effect is a serious challenge to urban sustainable development plans, the living environment of city inhabitants, and the liveability of urban spaces [5, 9]. Its adverse effects include increased energy use for cooling, overloading the power grid, and contributing up to 10% of a city's electricity consumption [2]; heightened emissions of pollutants and greenhouse gases; risks to human health and comfort, exacerbating heat-related morbidity and mortality, especially during heat waves; and poor water quality due to warmed stormwater runoff [10].

India faces intense urban and industrial growth as an emerging nation, resulting in tremendous temperature changes and enhanced weather extremes [9, 10]. According to the 2011 Census, India had about 31% of its population living in towns, which is estimated to rise to 40% by 2030 [10]. This fast growth has enhanced surface temperatures (STs) over contiguous rural areas during the past three to four decades [9]. Most studies suggest that UHI intensity in different Indian cities is maximum at night, and intensity values recorded vary from 2.0°C to 10.3°C, reflecting a distinct manifestation of a positive UHI over different local climate regimes [9, 10]. The growing issue of heat in India is driven by severe heat-related deaths, and the International Labour Organization has gauged that India lost 4.3% of working time to heat stress in 1995, which is expected to rise to 5.8% by 2030, equaling 34 million lost employment opportunities [2]. Cities such as Bengaluru and Hyderabad tend to have increased UHI-affected zones over the years because of urbanization and the utilization of concrete structures to substitute natural cover, with maximum annual UHI intensities of 4.65–6.69°C for Bengaluru and 5.74–6.82°C for Hyderabad [8]. Chennai, the most urbanized district of Tamil Nadu, has seen its built-up area increase from 48% in 1985 to 74% in 2015. The urbanization has led to high values of nighttime land surface temperature (LST) and UHI intensity, increasing from approximately 2.5°C in 2013 to about 3°C by 2023 [2, 10]. Delhi, a UHI hot spot, has experienced UHI intensities of up to 16.7°C during summer and 7.4°C during winter. Nighttime UHI has resulted in temperature rises of 4–7°C over the central regions compared to the rural areas [10].

Geospatial technologies like remote sensing (RS), Geographic Information Systems (GIS), and applications like Google Earth Engine (GEE) are crucial in solving such complex problems. These technologies provide accurate measurements of LST in cities and spatiotemporal feature extraction of the impact of surface urban heat island (SUHI) [11]. Mapping spatiotemporal and persistent urban heat islands (PUHI) is helpful for landscape architects and urban planners, as it provides excellent insights into preventing the SUHI phenomenon, building ecological civilization cities, and designing “liveable cities” [12]. Such a detailed analysis allows for heat-vulnerable hotspot identification at a high level of detail, which informs

targeted interventions like afforestation, water body restoration, and low-impact urban planning. It is essential to comprehend the intricate relationships between variance, persistence, and mean temperature to design future cities and manage heat, especially in towns with significant mean UHI effects, minor temperature variances, and high thermal inertia. This data-driven policy anchors sustainable urban development policies, ensures equitable interventions, and promotes resilience in the face of increasing temperatures.

2. Materials and methodology

2.1 Methodological framework

This study employs a comprehensive geospatial analysis framework executed entirely within the GEE cloud-computing platform to investigate the spatiotemporal dynamics of the urban thermal environment in Coimbatore, India. The primary objective is to leverage a multiyear time-series of satellite imagery to quantitatively map the SUHI effect and subsequently identify and delineate areas of PUHI. The overall workflow is systematically structured into five distinct stages: (1) definition of the study area; (2) acquisition of satellite data; (3) derivation and calibration of LST; (4) quantification and spatial zonation of the SUHI phenomenon; and (5) a robust spatiotemporal statistical analysis to identify persistent heat island patterns. This methodological approach is designed to be transparent, reproducible, and scientifically rigorous, ensuring the findings are valid and verifiable.

2.2 Study area

The study focuses on the Coimbatore City Municipal Corporation (CCMC) in Tamil Nadu, India. It is the state's second-largest city and is also known as the "Manchester of South India" because of its thriving textile industry. Coimbatore City is a vast urban metropolis in western Tamil Nadu, India, along the Kerala state border [13]. The corporation spans 257.04 km², including the surrounding townships, town panchayats, and village panchayats (**Figure 1**). The corporation has been subdivided into five administrative zones and 100 wards, indicating its management complexity. The city lies along the banks of the Noyyal River, a tributary of the Cauvery, originating from the Velliangiri Hills of the Western Ghats and forming the city's southern border. Geographically, CCMC varies between 10°54'57" N and 11°6'12" N latitudes and 76°51'22" E and 77°4'1" E longitudes [13]. The city is surrounded by the Western Ghats to the west and the Nilgiris Biosphere Reserve to the north, and thus has a unique ecological setting [14]. Topographically, the district is an upland plateau with rolling topography, dotted with hill ranges and hillocks, and is gently sloping toward the east. The city's average elevation is 460.60 m above mean sea level (MSL) [15]. At the same time, the Palghat Gap to the west serves as a midzone physiographic corridor for climatic interaction and human migration. The city has nine large lakes, such as Singanallur, Kuruchi, and Valankulam [16]. The lakes play a significant role in the environment and water supply, recharging groundwater and making the city sustainable [13]. The city experiences a tropical climate, at times semi-arid and sometimes humid, with temperatures ranging from 11.7°C to 42.6°C. It receives approximately 650–700 mm of rainfall annually, with nearly half (47%) coming from the northeast monsoon [14].

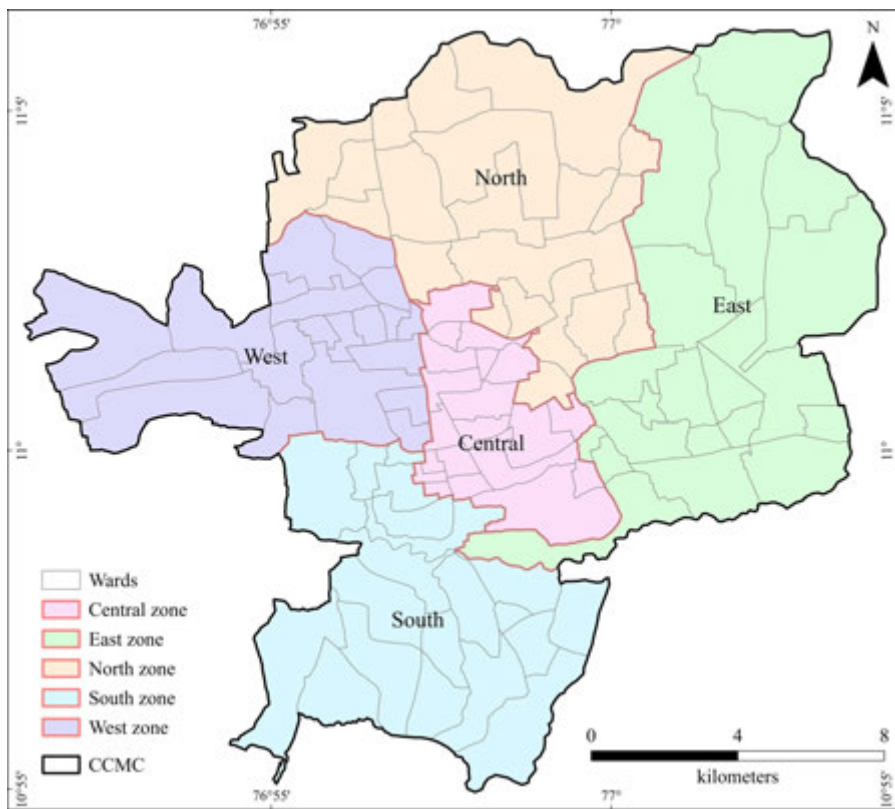


Figure 1.
Coimbatore City Municipal Corporation (study area).

2.3 Satellite data acquisition and preprocessing

2.3.1 Google Earth Engine

All data retrieval and preprocessing were conducted using the GEE platform. GEE is a planetary-scale, cloud-based platform designed explicitly for the scientific analysis and visualization of large geospatial datasets [17]. Its selection for this study was a deliberate methodological choice driven by several key advantages. GEE provides direct access to a multipetabyte catalog of analysis-ready satellite imagery, including the complete Landsat archive, thereby avoiding manual data download and storage, which would be prohibitive for a multidecade, regional-scale analysis [18]. This approach not only enhances computational efficiency but also fundamentally improves the study's transparency and reproducibility, as the entire analytical code can be shared and executed by other researchers on the same platform with identical data, minimizing discrepancies arising from different local computing environments [19].

2.3.2 Landsat 8 Collection 2 Level-2

The primary data source for this research is the Landsat 8 operational land imager (OLI) and thermal infrared sensor (TIRS) Collection 2 Level-2 science product

(L2SP). The decision to use this specific data product is critical for ensuring the scientific validity of the results. Collection 2 significantly advances over previous collections, offering improved geometric accuracy and enhanced radiometric calibration, essential for reliable time-series analysis [20]. The Level-2 processing level indicates that the data are delivered as “analysis-ready,” having been atmospherically corrected by the US Geological Survey (USGS) to produce surface reflectance (SR) and ST products. This preprocessing, performed using the validated land surface reflectance code (LaSRC) for SR and a single-channel algorithm for ST, corrects for the confounding influences of atmospheric absorption and scattering, providing a more accurate representation of conditions at the Earth’s surface compared to uncorrected Level-1 data.

The temporal scope of the analysis spans from 2014 to 2024, with a two-year gap. To isolate the period of maximum thermal stress and minimize seasonal variability, the image collection was filtered to include only acquisitions from the premonsoon summer season in southern India, defined as the months from March to May. This period is characterized by high solar insolation and minimal cloud cover, under which the SUHI effect is typically most pronounced. Only Tier 1 (T1) images were included in the analysis, as these data meet the highest geometric and radiometric quality standards.

2.3.3 Cloud and cloud shadow masking

A critical preprocessing step in any optical or thermal RS analysis is accurately identifying and removing pixels contaminated by clouds and their shadows, which can introduce significant errors in LST and vegetation index calculations. For this study, a cloud masking function was developed and applied to every image in the time series. This function utilizes the QA_PIXEL band provided within the Landsat 8 L2SP product. This ensures that the LST and SUHI calculations are based solely on clear-sky land surface observations.

2.3.4 Seasonal image compositing

The filtered and cloud-masked image collections were aggregated using a median composite technique to generate a single, spatially complete, and representative cloud-free image for each summer season within the study period. For each pixel location within the boundary, this method calculates the median value from all valid observations acquired during that year’s March-to-May window. Using a median reducer is a standard and robust practice in time-series analysis, as it is statistically less sensitive to extreme outliers than a mean reducer. This process results in five high-quality annual composite images for 2014, 2016, 2020, 2022, and 2024. No suitable image could be derived for 2018, which has been exempted from the study. This forms the basis for the LST and SUHI analysis.

2.4 Derivation of land surface temperature

This study directly utilizes the high-quality, precalculated LST product provided by the USGS as part of the Landsat 8 dataset, specifically the ST_B10 band. This approach was chosen over manual LST calculation to enhance accuracy and reduce methodological uncertainty. However, this method introduces

significant uncertainty, particularly in complex urban environments where the land cover is a heterogeneous mosaic of various materials with widely differing emissivity values.

The raw digital number (DN) values of the ST_B10 band were converted to LST in degrees Celsius (°C) using a linear scaling equation. First, the provided scale factor and offset value were applied to convert the DNs to LST in Kelvin (K). Subsequently, the result was converted to Celsius by subtracting the absolute zero offset (273.15). The complete transformation, as applied in GEE, is represented by the following equation:

$$LST (^{\circ}\text{C}) = (DN_{ST_B10} \times 0.00341802) + 149.0 - 273.15 \quad (1)$$

Eq. (1) was applied to each seasonal composite image to generate a time series of LST maps.

2.5 Delineation of SUHI

The SUHI is calculated from LST using Eq. (2) [21].

$$SUHI = \frac{T - T_{mean}}{SD} \quad (2)$$

where T = LST, T_{mean} = mean of the retrieved LST of the study area, and SD = standard deviation. SUHI is divided into five classes of <-1.5 , -1.5 to -0.5 , -0.5 to 0 , 0 to 0.5 , and >0.5 .

2.6 Extraction of persistent SUHI

To identify areas that consistently experience high thermal stress, a temporal frequency analysis was conducted on the SUHI maps from five selected years: 2014, 2016, 2020, 2022, and 2024. This method delineates PUHI by quantifying how often a specific location is classified as a significant heat island over the analysis period. The methodology involved a two-step process of binarization and temporal aggregation.

First, each of the five annual SUHI raster layers was reclassified into a binary map to isolate significant SUHI hotspots. A threshold was applied, where all pixels with a SUHI value greater than 0.5 were assigned a new value of 1, representing the presence of a hotspot. All pixels with a SUHI value of 0.5 or less were assigned a value of 0, indicating the absence of a significant hotspot for the season of that year. This step produced five distinct binary raster layers, each highlighting the spatial extent of the most intense SUHI effect for the given year.

Second, a raster calculator tool summed these five binary layers together. This temporal aggregation results in a final PUHI map where the value of each pixel represents the frequency with which that location was identified as a SUHI hotspot over the five years. The pixel values in the final output raster range from zero to five. A pixel with a value of five indicates a highly persistent SUHI, as it was classified as a hotspot in all five of the analyzed years. Conversely, a pixel value of zero indicates that the location never reached the hotspot threshold in any of the selected years. This frequency-based approach provides a precise and quantitative measure of SUHI persistence, allowing for the direct identification of the most consistently heat-stressed areas within the city.

2.7 Extraction of persistent SUHI

A zonal analysis was performed to further examine the spatial distribution of thermal stress across different administrative and planning units within Coimbatore. This technique calculates summary statistics for raster pixel values within predefined zones, typically represented by vector polygons. In this study, the primary objective of the zonal analysis was to compute the mean LST for each administrative zone and ward within the city.

The analysis utilized the annual LST raster maps as the value input and the official vector boundary files for Coimbatore's zones and wards as the zone input. For each year's LST map, the Zonal Statistics tool was executed twice: once with the zone boundaries and once with the ward boundaries. The tool aggregates all LST pixel values falling within the boundary of each specific zone and ward and calculates the mean. This process results in an output that links each administrative unit to its corresponding mean LST for that year, providing a quantitative measure of the average thermal condition at a localized, policy-relevant scale. This allows for direct comparison of thermal loads between different administrative areas and helps identify which zones or wards are experiencing higher average temperatures.

3. Results and discussion

3.1 Zone-wise mean LST

The calculated data summarize the mean LST in degree Celsius across the five administrative zones of the city – Central, East, North, South, and West – for the years 2014, 2016, 2020, 2022, and 2024. This zonal analysis provides a high-level overview of the thermal dynamics across broad sections of the city (**Figure 2**).

3.1.1 Consistently hottest zones

The North and East zones consistently exhibit the highest mean LSTs across most observed years. In 2014, the North zone recorded the highest temperature at 52.20°C, a trend that continued in 2016 (47.01°C) and 2022 (47.24°C). The East zone also consistently registered high temperatures, often ranking second-highest. This suggests that these zones may have a higher concentration of heat-retaining surfaces, such as dense built-up areas, and less vegetation cover than other zones.

3.1.2 Coolest zone

The Central zone consistently recorded the lowest or second-lowest mean LST in four out of the five years analyzed. In 2014, it had the lowest LST at 49.09°C, and it remained the coolest zone in 2020 (42.15°C) and 2024 (41.13°C). This could indicate a greater presence of green spaces, water bodies, or different urban morphology in the central part of the city, which helps mitigate extreme surface heat.

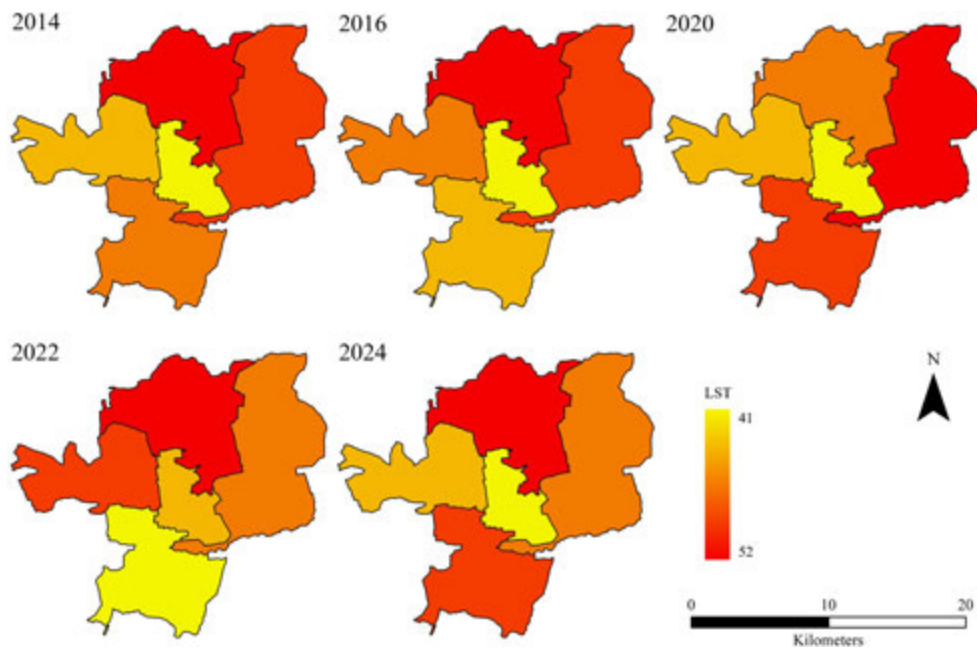


Figure 2.
Zone-wise mean LST.

3.1.3 City-wide temperature fluctuations

There is a noticeable city-wide trend in temperature fluctuations over the years. All five zones show a similar pattern: high temperatures in 2014, a decrease in 2016, a further significant drop in 2020, a rebound in 2022, and another drop in 2024. 2020 has the lowest mean LST across all zones, followed closely by 2024. This pattern suggests that broader climatic conditions or specific atmospheric conditions during the satellite data acquisition for those years likely influenced the overall thermal landscape of the entire city.

3.1.4 Magnitude of temperature difference

The temperature difference between the hottest (North) and coolest (Central) zones was most pronounced in 2014, with a gap of 3.11°C. This highlights significant intracity thermal variation even at a broad zonal scale. While the gap narrows in other years, the North zone consistently remains hotter than the Central zone, reinforcing the idea of persistent spatial patterns in the city's thermal environment.

3.2 Ward-wise mean land surface temperature

The ward-wise data provides a much more granular view of the thermal environment, revealing significant temperature variations at the neighborhood level across 100 wards for the same five years. This detailed analysis is crucial for identifying specific local hotspots and cool spots that are averaged out in the broader zonal analysis (**Figure 3**) [22, 23].

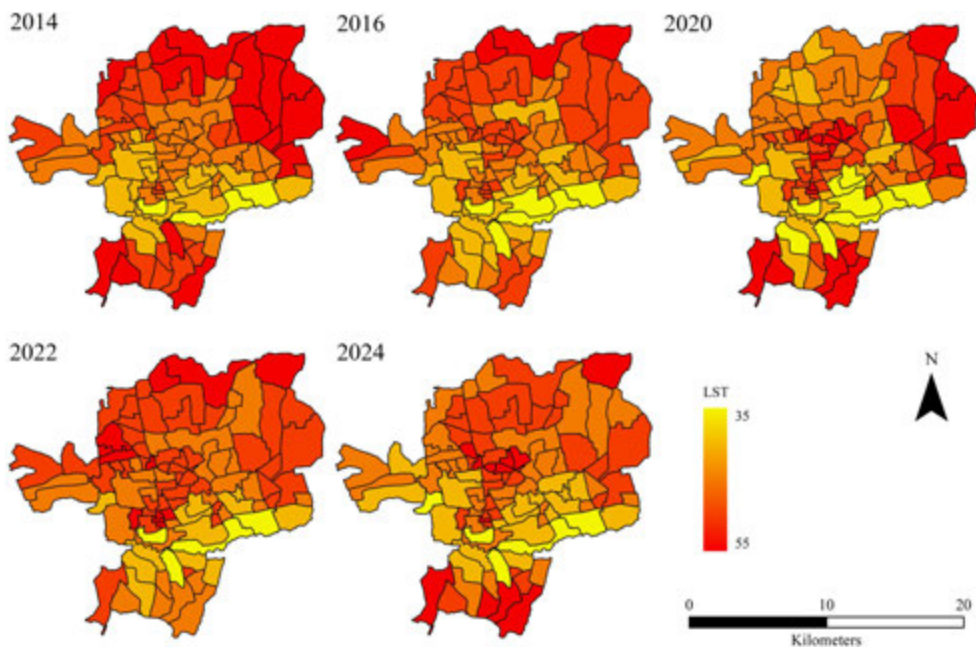


Figure 3.
Ward-wise mean LST.

3.2.1 Identification of extreme hotspots

Certain wards consistently stand out as extreme thermal hotspots. Ward 28 and Ward 33 are among the hottest wards across multiple years. Ward 28 recorded a peak temperature of 54.09°C in 2014, one of the highest in the dataset. Ward 33 showed exceptionally high temperatures in 2016 (50.65°C) and 2022 (50.32°C), significantly exceeding the city-wide average in those years.

Other wards like 4, 26, 36, and 89 also frequently appear in the top tier for high temperatures, indicating persistent heat stress in these specific localities. For instance, Ward 4 registered 53.54°C in 2014. These areas likely correspond to dense industrial zones, commercial centers, or residential areas with minimal green cover.

3.2.2 Identification of consistent cool spots

Conversely, a few wards consistently exhibit much lower LSTs, acting as relatively incredible islands within the urban matrix. Ward 85 is the most prominent cool spot, recording the lowest LST in all five years, with temperatures dropping as low as 35.38°C in 2024. Its highest recorded temperature was only 44.24°C in 2014, a value lower than the mean temperature of many other wards.

Ward 63 and Ward 75 also consistently show very low LSTs. For example, in 2024, their temperatures were 37.26°C and 38.11°C, respectively. These wards almost certainly contain large parks, extensive vegetation, and water bodies, or they are located on the cooler, less-developed urban fringe.

3.2.3 Extreme intracity thermal variation

The ward-level data reveal a dramatic range of temperatures within the city for any given year. In 2014, the difference between the hottest ward (Ward 94 at 55.17°C) and the coolest ward (Ward 85 at 44.24°C) was nearly 11°C. This vast difference underscores the highly localized nature of the UHI effect and demonstrates that a resident’s thermal exposure can vary significantly over just a few kilometers.

3.2.4 Temporal trends in specific wards

While the city as a whole shows a fluctuating temperature trend, individual wards display unique patterns. For example, Ward 33 shows a less pronounced drop in 2020 than other wards, maintaining a relatively high LST of 46.35°C. This suggests that this ward’s land cover and urban form make it resiliently hot, regardless of broader cooling trends. In contrast, wards like Ward 20 and Ward 71 consistently decline, with their 2024 temperatures being the lowest in the observed period, suggesting potential greening or land-use changes that have mitigated surface heat over time.

3.3 Mapping persistent SUHI

3.3.1 Spatiotemporal distribution of SUHI intensity

The five maps illustrate the spatial distribution and intensity of the SUHI effect for 2014, 2016, 2020, 2022, and 2024 (Figure 4). The color scale represents the

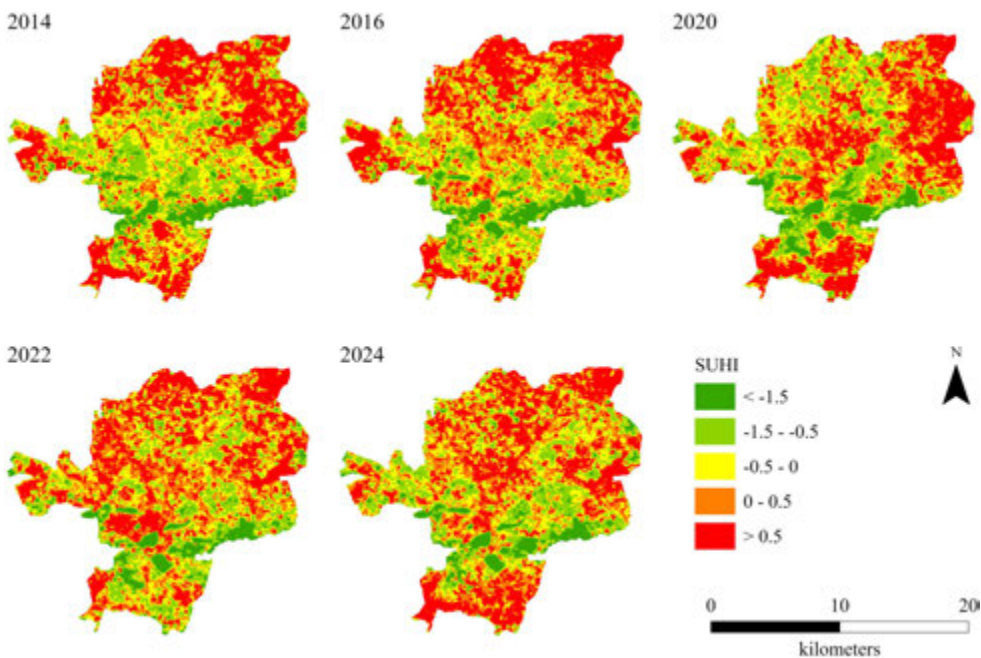


Figure 4.
Spatiotemporal distribution of SUHI intensity.

deviation from the city’s mean temperature for that year, ranging from the coolest to the most intense heat island areas.

Across all five years, a consistent geographical pattern is evident. The most intense SUHI areas (red and orange) are predominantly located in the northern and central-eastern parts of the city. These areas correspond to the urban core and densely developed zones. Conversely, the coolest areas (shades of green) are consistently found along the southern and western peripheries, likely representing areas with more vegetation, water bodies, or less dense development [24, 25]. While the spatial pattern is stable, the overall intensity of the SUHI effect varies from year to year. The 2014, 2016, and 2022 maps show a greater extent and intensity of red and orange pixels, indicating more severe heat island effects in those years. In contrast, the maps for 2020 and 2024 appear cooler overall, with a visible reduction in the most intense (red) category and a greater prevalence of yellow and light green areas. This year-to-year fluctuation likely reflects broader meteorological conditions influencing the entire region during the specific days the satellite imagery was captured.

3.3.2 SUHI hotspot distribution

The complex thermal landscape has been reclassified into two categories: SUHI (red), representing areas with a normalized temperature value greater than 0.5, and non-SUHI (light gray). These maps effectively isolate the most significant hotspot areas for each year.

These maps clearly delineate the spatial footprint of the most significant heat island areas in each specific year. They are the foundational layers aggregated to create the final PUHI map (**Figure 5**). Like the intensity variations, the total area

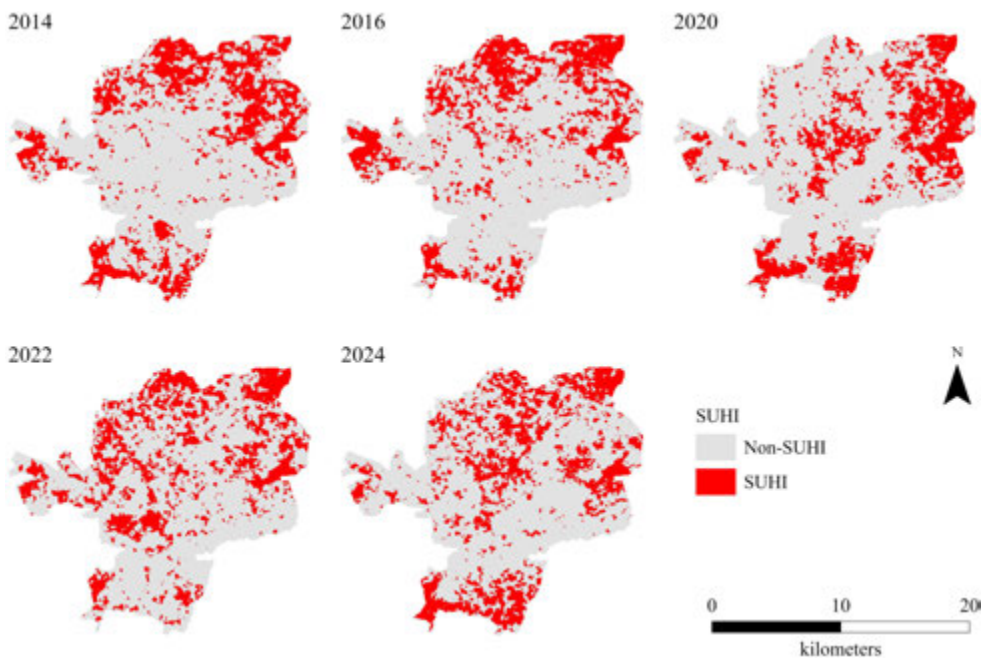


Figure 5.
Binarization of SUHI and non-SUHI.

covered by SUHI hotspots fluctuates annually. The years 2020 and 2024 show fewer red areas compared to 2014, 2016, and 2022 [26]. This confirms that fewer areas reached the critical heat threshold during these cooler years. The most critical insight from this series is the high degree of spatial consistency in the location of the hotspots. Despite fluctuations in their total area, the same clusters in the northern, eastern, and southern parts of the city repeatedly appear as SUHI zones across the years. This visual recurrence demonstrates the concept of persistence. It confirms that specific neighborhoods are chronically prone to high STs, justifying their classification as PUHIs in the final aggregated map [27].

3.3.3 PUHI frequency

The map (**Figure 6**) provides a detailed, quantitative visualization of the persistence of the SUHI effect by showing the frequency with which any given area was classified as a SUHI hotspot over the five analyzed years (2014, 2016, 2020, 2022, and 2024). The color ramp indicates this frequency, ranging from zero for areas that were never a hotspot to five for areas that were a hotspot in all five of the selected years. This map results from summing the five individual binary SUHI maps shown in the previous images. It offers a clearer view than the simple binary PUHI map by illustrating the gradient of thermal stress persistence across the city [28].

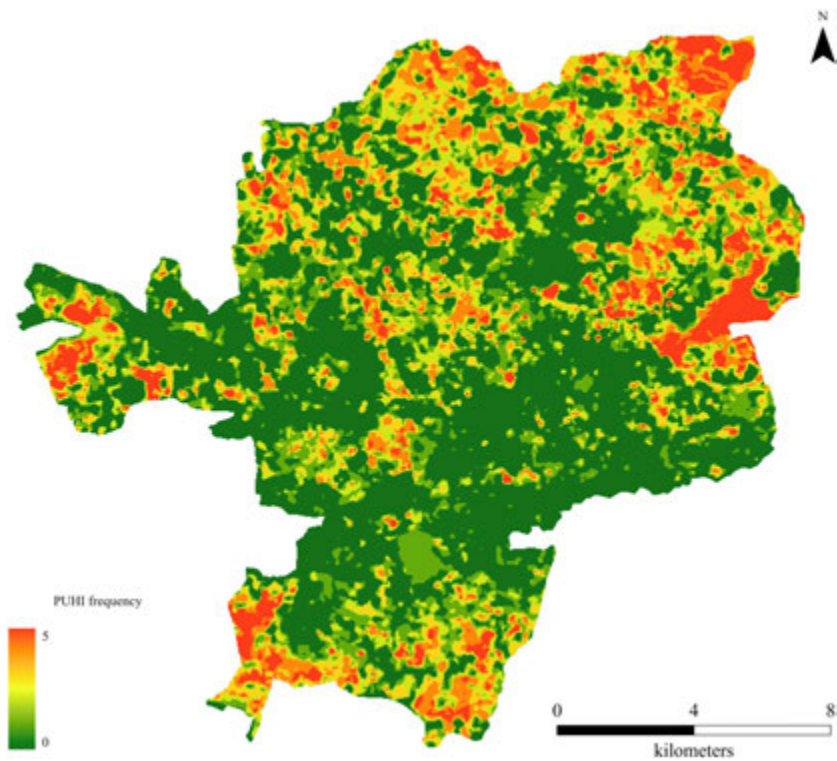


Figure 6.
Frequency map of PUHI.

The bright orange and red areas are the most critical, representing the core of the city's heat island problem. These locations have been hotspots in four or all five analyzed years. Spatially, these highly persistent zones are concentrated in several distinct clusters, most notably in the northern, central-eastern, and southeastern parts of the city. These locations are unequivocally the most heat-stressed neighborhoods and require the highest priority for mitigation efforts. The light green and yellow areas represent locations classified as hotspots in only one or two of the five years. These are sporadic or intermittent hotspots. While not as chronically stressed as the high-frequency zones, their presence indicates a vulnerability to heat island formation under certain conditions. These areas could be monitored for worsening trends. The large dark green areas represent the city's most thermally stable and calm parts. These locations never reached the SUHI hotspot threshold in five years. They are predominantly found along the southern and western fringes of the city, which, as seen in the annual SUHI intensity maps, consistently correspond to areas with higher vegetation cover. These zones act as the city's "cool islands" and are vital for urban climate regulation [29, 30]. The areas with frequency greater than or equal to four were considered persistent heat areas. Unlike a simple binary map, this frequency analysis reveals a transparent gradient. The most persistent hotspots (orange/red) often form the core of a larger area of less frequent hotspots (yellow/light green). This suggests that the UHI effect radiates outward from core drivers, such as dense industrial or commercial zones, with decreasing persistence toward the periphery. This detailed view allows for a more sophisticated planning approach, where the intensity of an intervention can be matched to the severity and persistence of the heat problem.

3.3.4 Mapping of PUHI

The map (**Figure 7**) displays the final output of the study, illustrating the spatial distribution of PUHI across the city. The areas marked in red represent PUHI zones, which have consistently registered as significant heat hotspots over the multiple years analyzed. The light gray areas are classified as non-PUHI, meaning they did not exhibit the same sustained high temperatures.

The PUHI zones are not concentrated in a single central core but are distributed in fragmented clusters throughout the city. Significant concentrations of these persistent hotspots exist in the study area's northern, eastern, and southern portions. The central and western parts of the city appear to have a lower density of PUHI areas. The pattern is characterized by numerous scattered patches of varying sizes rather than a single, monolithic heat island. This suggests that the factors driving persistent heat are localized and likely tied to specific land-use features, such as industrial areas, densely packed residential neighborhoods with little green space, or large commercial zones. This map is a critical tool for urban planners and policymakers. The red zones highlight the most chronically heat-stressed areas within the city. These are the priority locations for targeted heat mitigation interventions, such as increasing tree canopy, developing parks and green spaces, and implementing cool pavement and roofing technologies. The scattered nature of the PUHI suggests that a city-wide, decentralized greening strategy would be more effective than focusing on a single area.

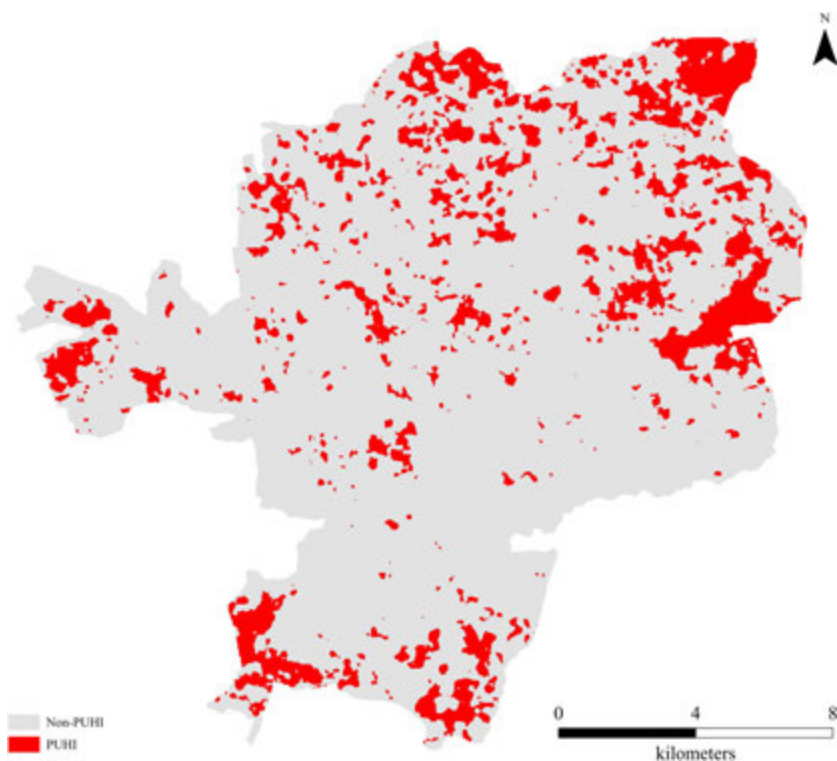


Figure 7.
Persistent urban heat island.

4. Conclusion

The study successfully identified and mapped the spatial and temporal dynamics of the SUHI effect in CCMC, culminating in the delineation of PUHIs. By leveraging a multiyear time series of Landsat 8 satellite data, the analysis revealed a consistent and deeply entrenched spatial pattern of thermal inequality across the city.

The annual SUHI intensity maps demonstrate that, while the overall thermal intensity fluctuates from year to year – likely influenced by broader climatic conditions – the geographic distribution of hot and cool zones remains remarkably stable. The northern and central-eastern parts of the city consistently exhibit the highest SUHI intensity, corresponding to the most intensely developed urban areas. Conversely, the southern and western peripheries, characterized by more vegetation and less dense construction, consistently act as the city’s cooler zones. This persistent spatial pattern underscores that the urban landscape’s physical characteristics are the primary drivers of the SUHI effect.

Identifying PUHI through a temporal frequency analysis provides the most critical insight for urban planning. Rather than a single, uniform heat island, Coimbatore’s thermal landscape is characterized by a scattered archipelago of persistent hotspots. The frequency map, in particular, offers a nuanced view, distinguishing between sporadic hotspots and the most chronically heat-stressed areas classified as hotspots in four or all five of the analyzed years.

The zonal and ward-wise LST analysis strongly reinforces this conclusion. At a broad administrative level, the North and East zones consistently recorded the highest mean LSTs, aligning with the spatial patterns observed in the maps. However, the ward-level data reveals the proper granularity of the issue, showing extreme intracity temperature variations of up to 11°C in a single year. This analysis pinpoints specific wards (28, 33, and 94) as severe and recurring hotspots. In contrast, others (notably Ward 85) serve as consistent, incredible islands, likely due to the presence of significant green spaces or water bodies.

This research provides a clear, data-driven roadmap for targeted climate action. Identifying specific, persistent heat islands at the ward level moves beyond general understanding to provide actionable intelligence. These PUHI zones are the priority areas where strategic urban greening, increasing tree canopy, implementing cool materials for pavements and roofs, and developing public green spaces are most urgently needed. By focusing mitigation efforts on these chronically affected neighborhoods, city planners and policymakers can most effectively enhance thermal comfort, improve public health outcomes, and build a more sustainable and resilient urban environment for all residents.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 6

The Cologne Forestry Laboratory – A Living Lab on Urban Reforestation

Frank Lohrberg

Abstract

This chapter discusses the “Cologne Forestry Laboratory,” a living lab focused on urban reforestation. The laboratory occupies 30 hectares of former agricultural land in the western part of Cologne and showcases four distinct approaches to reforestation in an urban context: an “energy forest” dedicated to climate-neutral energy production, a “beauty forest” sponsored by citizens, a “climate forest” featuring tree species tested for their adaptability to climate change, and a “wilderness forest” that is entirely left to nature. Located adjacent to the renowned Cologne Green Belt – an exemplary model of urban greening policies from the last century – the laboratory was established in 2010 based on a landscape architecture design proposal. Its aim is to transform the forest into a public space with esthetic appeal, providing information on reforestation while welcoming visitors through improved accessibility. As a living lab, it actively involves stakeholders and citizens, invites students, and engages researchers in studying the development of the forests. The chapter provides an overview of the Cologne Forestry Laboratory and its various components. It explains the experiments conducted within each section and presents their initial results. The findings highlight that reforestation in urban areas significantly benefits from design strategies that convert these areas into public spaces with visible and accessible features.

Keywords: urban forestry, reforestation, living lab, short rotation plantation, artistic intervention.

1. Introduction

Cologne is Germany’s fourth-largest city, with over 1 million inhabitants, and it hosts the first forest laboratory in a German metropolitan area. The concept for this laboratory emerged as part of the “Regionale Köln-Bonn 2010,” a funding program initiated by the federal state of North Rhine-Westphalia [1]. Its objective was to assist municipalities in the greater Cologne area and Bonn to the south for a better coordination of their spatial development.

In Germany, municipalities play a significant role in planning; they largely determine land use and spatial development. However, since planning typically ends

at municipal boundaries, regional concerns are often overlooked. This issue is particularly pronounced in linear infrastructures such as waterways, recreational routes, and urban green corridors.

This is precisely where the funding program of 2010 provided a crucial impetus for the city of Cologne and its western neighboring municipalities to engage in collaborative planning. The “Regio Grün” concept, which addresses “Regional Green,” inspired the development of an open space system that connects Cologne’s green belts with the surrounding areas through new radial open space corridors [2].

Cologne already features two concentric green belts – an “inner” and an “outer” green belt – planned and established in the 1920s. However, these were primarily designed for the city’s purposes, with little regard for the needs of municipalities in the broader region.

Since then, these areas have experienced several waves of suburbanization, leading to the growth of villages and towns, as well as the emergence of industrial estates and new transport routes. These developments have fragmented established structures, such as villages and agricultural lands, contributing to a phenomenon commonly criticized as urban sprawl.

“Regio Grün” aims, as shown in **Figure 1** [2], to address this issue by connecting previously isolated open spaces to create regional green corridors. These corridors bear evocative names such as “Zu neuen Energien” (“Toward New Energies”) and “Die Rheinischen Gärten” (“The Rhenish Gardens”). Such names reflect “Regio Grün’s” objective not only to protect regional open spaces but also to enhance their value, making them visible and accessible to the public.

One of the open space corridors extends from the Cologne Outer Green Belt to the edge of the “Ville,” a range of hills located west of the city. While both the green belt and the Ville are predominantly forested, the area in between has been largely

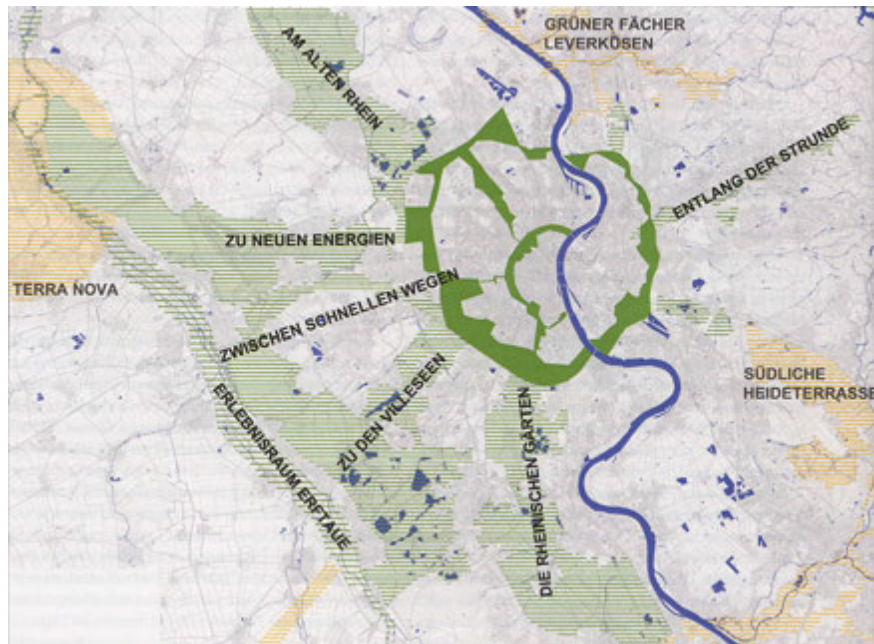


Figure 1.
Regio Grün – Basic Idea [2].

deforested for centuries. The soil in this region is very fertile and was traditionally used for agriculture. Today, it is also characterized by supra-regional transport routes, including motorways and rail lines.

One planned open space corridor, named “Zwischen schnellen Wegen” (meaning “In Between Fast Routes”), occupies a unique position between a motorway to the south and the Cologne–Brussels railway line to the north. This concept conveys that even amidst major infrastructure, there remains space for reforestation, landscape appreciation, and opportunities for walking or biking into the surrounding region.

However, this initiative goes beyond merely concealing roads with greenery; it seeks to actively incorporate these transport routes into the landscape design. The goal is to present them as an integral part of the urban environment – almost as if they were a “natural” aspect of it [3].

With support from the “Lebendige Stadt” foundation [4], the city of Cologne and its surrounding municipalities further developed the open space corridor by commissioning the landscape planning office “lohrberg stadtdlandschaftsarchitektur,” based in Stuttgart. The planning process particularly emphasized woodland and forest elements. As illustrated in **Figure 2**, [5] the goal was to create a “forest bridge” connecting the Cologne Outer Green Belt to the Ville. This initiative aims to meaningfully integrate existing wooded areas, such as roadside greenery and tree-lined avenues, thereby enhancing both ecological and esthetic qualities.

A 25-hectare area of farmland on the edge of Cologne’s Outer Green Belt was identified as the eastern “bridge abutment” of the forest bridge. The adjacent Cologne Outer Green Belt features a tall mixed deciduous forest, which, upon closer inspection, was found to be younger than its appearance might suggest. This forest was planted by the city of Cologne in the 1960s to extend the historic Outer Green Belt, responding to the open-space planning needs of that era. The new forest aimed to provide protection from emissions generated by open-cast lignite mining located to the west of the city and to meet the growing recreational needs of the population.

With this “innovative character” of the green belt in mind, several workshops involving representatives from local authorities sparked discussions about what current challenges an urban forest should address. This led to the conception of a “forest laboratory” for Cologne, which was developed and realized step by step until 2010.



Figure 2.
“Forest Bridge”: Basic idea to link existing greenery elements. Lohrberg Stadtdlandschaftsarchitektur, 2007 [5].

2. The forest laboratory as a place for experiments

The Cologne Forest Laboratory represents an experimental approach to addressing the question: How can an agricultural field adjacent to a motorway be transformed into a forested public space, specifically a new type of urban park? This fundamental question is accompanied by several sub-questions, leading to the division of the forest laboratory into four components, as shown in **Figure 3** [6], an “energy forest” (1) that seeks answers related to climate-neutral energy supply, a “beauty forest” (2) that experiments with diverse forest esthetics and community engagement, a “climate forest” (3) that investigates stress-resistant tree species in the context of climate change, and a “wilderness forest” (4) that explores reforestation possibilities when an area is left to nature.

Covering 6.3 hectares, the energy forest constitutes the largest portion of the area. It features fast-growing tree species such as balsam poplar (*Populus balsamifera*), black poplar (*Populus nigra*), and various species of willow (*Salix* spp.), which are planted in long rows and harvested in “short rotation” cycles of 4 to 7 years. When the trunks reach a thickness comparable to that of an arm, they are cut close to the ground using a forage harvester, with another vehicle collecting the material (see **Figure 4** [6]). A few weeks after being cut down, these trees regenerate by sprouting again.

The harvested material is processed into wood chips to contribute to a CO₂-neutral energy supply. The forest laboratory aims to identify suitable tree species and tailored harvesting methods, while also exploring the extent to which urban citizens accept short rotation plantations.



Figure 3.
Cologne Forest Laboratory. Plan with four components. Lohrberg F, Matros J, 2013 [6].



Figure 4.
Harvesting the energy forest in February 2014. © Matros J [6].

The **beauty forest** serves as an esthetic and botanical experiment, covering an area of 3.7 hectares. It features tree species that are particularly striking due to their botanical characteristics, such as foliage or trunk coloration. The selected species include yew (*Taxus baccata*), sand birch (*Betula pendula*), sweet chestnut (*Castanea sativa*), field maple (*Acer campestre*), chequer tree (*Sorbus torminalis*), sweet cherry (*Prunus avium*), coastal fir (*Abies grandis*), and Douglas fir (*Pseudotsuga menziesii*). Unlike conventional mixed forests, this beauty forest combines only two tree species at a time to create specific forest patterns. For example, how do chequer trees and wild cherries harmonize? What is the visual effect of sweet chestnuts growing alongside field maples? How does the light-colored bark of sand birches contrast with the dark green leaves of yews? Based on a specialized planting scheme, the forest images are in constant flux – changes that can be most easily appreciated by strolling along a small path that runs lengthwise through the beauty forest.

The **climate forest** addresses climate change, one of the biggest challenges that needs to be tackled worldwide, but also in German cities and municipalities. Densely populated cities like Cologne are experiencing general warming and an increase in extreme weather events. The concentration of buildings creates a heat island effect that not only stresses urban residents but also affects city forests and trees. Consequently, the forest laboratory is investigating tree species that are resistant to drought and low humidity. Could species such as walnut (*Juglans regia*), paulownia (*Paulownia tomentosa*), downy oak (*Quercus pubescens*), coastal fir (*Abies grandis*), or chequer tree (*Sorbus torminalis*) play a more prominent role in German urban forests in the future? To explore this question, six square groves measuring 50 × 50 meters have been planted, each featuring one of these specific tree species.

In contrast, the **wilderness forest** spans 4.5 hectares and allows for natural development to occur. This setting provides insights into how unmanaged forest areas evolve over time. Questions arise regarding the speed of reforestation: How quickly does this process take place? What ecological and esthetic qualities emerge?

How is “wilderness” perceived by the public? Studies from the Ruhr region – where succession forests are also being explored – indicate that while such forests are highly valued in academic circles, they can be criticized by local populations as “neglected areas” associated with the structural decline of the region [7].

3. Co-production of reforestation

In line with the concept of a living lab, the City of Cologne has explored innovative approaches to reforestation. It sought partnerships within the industry, finding collaborators such as Toyota Deutschland GmbH, which sponsored parts of the woodland planting and supported ongoing public relations efforts. Toyota has also incorporated the forest laboratory into its event management, organizing “forest-climate rallies” for children and young people. Interestingly, Toyota’s German headquarters is located not far from the forest laboratory, providing employees with the opportunity to benefit from their company’s engagement in their immediate surroundings – such as during a lunchtime walk.

Another industrial partner, RheinEnergie AG, a nationally operating energy company, volunteered to assist with the planting and maintenance of the energy forest. The company is primarily involved in brown coal mining west of Cologne, which is set to phase out in the coming years due to national climate policy initiatives. As a result, there is growing interest within the company in regenerative forms of energy production.

Citizens have also been given the opportunity to participate, particularly by donating toward tree planting – an initiative that not only has financial benefits but also helps foster a positive public perception of the project. In line with this effort, the Cologne Forest Administration maintains a website [8] that provides information about the aims and measures of the forest laboratory, announces guided tours, and offers tips on accessing the site via public transport. In addition, a blog allows foresters to report on current activities within the laboratory and respond to questions and suggestions from citizens.

4. The forest laboratory as a public place

These explanations highlight that the Cologne Forest Laboratory aims not only to serve as a test site but also to function as a well-connected public space. Its location adjacent to the Cologne Outer Green Belt supports this objective, as important north–south and east–west pedestrian and cycling routes intersect at the forest laboratory. In addition, a stop for the Cologne city railway is just a few minutes’ walk to the north.

The forest laboratory itself is designed as a public space. As illustrated in **Figure 5**, [9] a wide, paved path meanders through the site, allowing visitors – such as walkers, joggers, and cyclists – to explore the various areas. Narrower paths lead into the wooded sections. Information boards provide details about the different components of the park. Several strips of meadow structure the site and offer views from the green belt across to the motorway. Some visitors have expressed concern that the motorway should have been concealed by planting, especially since its noise impacts certain parts of the forest laboratory. However, the planners intentionally chose to incorporate



Figure 5.
Drone picture, 2016. © Schiefer H. [9].

traffic into the scenery. Their design did not aim for seclusion and tranquility; rather, it sought to explore whether interesting contrasts could be created between the compact, densely planted woodlands and the seemingly constant flow of traffic.

5. The forest laboratory in 2025

The Cologne Forest Laboratory was established in 2010, and by 2025, it will be possible to reflect on 15 years of initial experiences. From a forestry perspective, this is a relatively short time frame; however, some preliminary findings can be drawn, particularly concerning the integration of the forest laboratory into the urban context.

The short rotation plantations within the **energy forest** demonstrated impressive growth performance on the fertile loess soils. Poplars and willows – typical species for short rotation plantations – were harvested for the first time in 2014, just 4 years after planting. Two additional harvests followed, but they presented logistical challenges since no further short rotation plantations were established in the region as initially expected. Consequently, harvesting machines had to travel from far away. Furthermore, selling wood chips required a high level of coordination, as these materials needed to be temporarily stored before utilization. The yields varied and did not always cover the costs associated with harvesting. In addition to poplars and willows, robinias (*Robinia pseudoacacia*), elms (*Ulmus laevis*), and chestnuts (*Juglans regia*, *Juglans nigra*) have also been planted; however, these species have not yet been harvested due to their slower and more irregular growth rates. Willows become increasingly difficult to harvest after several cuttings, as the fresh shoots tend to be thinner. After the fourth harvest cycle, a decision will be made regarding whether the short rotation plantations should be cleared and replanted.

It was very insightful to observe the public's reaction to the growth and harvesting of the plantations. The Cologne plantations were among the first established in a German urban area, resulting in limited prior knowledge that could have helped predict how harvesting would be accepted. Initially, the plantations were viewed very favorably; the woody plants grew faster than those in other parts of the forest laboratory, making them an appealing feature. However, this positive perception changed abruptly in 2014 when the first harvest took place. Residents expressed their concerns to the city administration and through letters to local publications. Many citizens did not understand why the poplars and willows seemed to “disappear overnight”, leaving behind what they described as a “bare field.” In an accompanying study conducted by RWTH Aachen University [10], visitors to the forest laboratory were asked whether they saw the energy forest as an added value to the visual landscape. **Figure 6** [10] shows that positive answers were mainly received during the survey periods, which coincided with growth phases and especially following the plantation's regrowth (81.8%, $n = 44$). Immediately after harvesting,

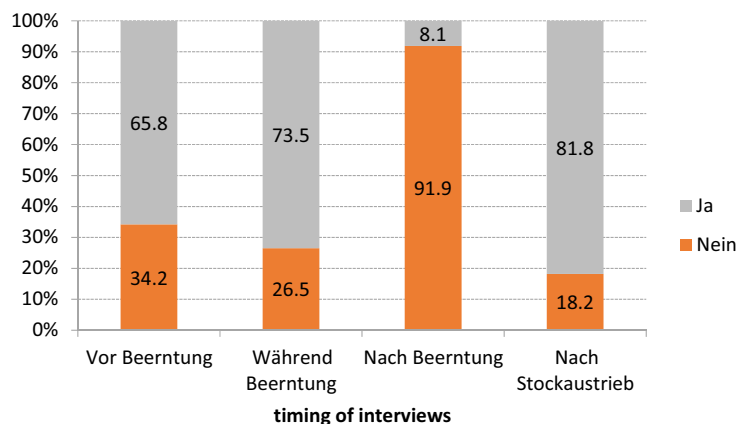


Figure 6.

Energy forest as added value to the visual landscape, ja = yes, nein = no ($n = 153$; before harvesting (*vor Beerntung*) $n = 38$, during harvesting (*während Beerntung*) $n = 34$, after harvesting (*nach Beerntung*) $n = 37$, after coppice regeneration (*nach Stockaustrieb*) $n = 44$; $p \leq 0.001$) [10].

the perception of appearance was generally negative, with 37 respondents at that time (91.9%, $n = 37$) feeling that the energy forest had a detrimental impact upon the landscape.

Remarkably, after the harvesting cycle, support for this new form of urban forest was even higher than at its inception. Two key processes contributed to this shift in perception. First, the trees quickly sprouted again, delighting visitors with their fresh greenery. Second, the City of Cologne effectively communicated the purpose of the harvesting, informing the public that, by harvesting, it generated enough energy to supply approximately 100 single-family homes for a year.

Based on the findings from this survey, the forest administration concluded that future harvests should be announced well in advance through press releases and updates on the forest laboratory's website.

In addition, it was decided to enhance communication with the public through artistic interventions. Since 2015, students from RWTH Aachen University have been invited every 2 years to participate in a week-long workshop on-site. During these workshops, students explore the laboratory and highlight its unique features. Under the supervision of the university's Institute of Landscape Architecture, they camp on-site, receive guided tours from foresters, and independently explore the area for inspiration to create their own interventions (see **Figure 7** [11]).

This collaboration has resulted in a series of artworks – including wooden tunnels, crowns, bridges, and sculptures – crafted from poplars, willows, and other tree species. For several days, these installations transform the appearance of the laboratory and facilitate discussions among students and visitors alike. The artworks also encourage visitors to engage more actively with the forest and possibly inspire them to create their own installations.

The short rotation plantations demonstrate remarkable resilience: what is cut down quickly regrows. Any structures built will eventually decompose or be removed during subsequent harvests. What remains are small paths created by visitors accessing these artworks. These paths have now formed a secondary network that allows visitors to navigate through various areas of the forest.

As a result of improved communication through the website and on-site installations, there was no criticism regarding subsequent harvesting. Consequently, the Cologne Forest Laboratory has demonstrated that short rotation plantations can be an acceptable form of forest in urban areas.

The **beauty forest** has been very well received by the local population. Fifteen years after its establishment, many visitors perceive it as having “always been there.” As mentioned earlier, the city of Cologne adopted a new approach to financing the laboratory. In particular, trees and shrubs in the beauty forest were donated by residents as part of a newly launched campaign called “A Forest for Cologne.” People were invited to make donations of €150 or more, which corresponds to 25 square meters of woodland. The experience with this financing model has been highly positive. While the beauty forest was initially considered the “1st Forest for Cologne” in 2010, with nearly 15,000 trees planted, the city's forestry administration has since managed to plant an additional 40,000 trees and is already working on what will be known as the “6th Forest for Cologne” by 2025 [12]. It is evidently important for the forestry administration to consolidate donations and civic engagement to sustain its reforestation efforts.



Figure 7.
Forest workshop conducted by RWTH Aachen University in 2016. © Matros [11].

As previously explained, the **climate forest** consists of six groves, each composed of a single tree species. The goal is not only to gain insight into the growth performance of these species but also to present them attractively to visitors. So far, all tree species have exhibited different yet consistently strong growth performance. After 15 years of growth, these small forests are clearly visible within the overall landscape of the forest laboratory – especially following the harvesting of short rotation plantations. Each grove increasingly offers a unique experience for visitors; for instance, with its lavish blossoms in late spring, the Paulownia grove attracts numerous insects as well as people. The coastal fir grove stands out due to its dark and dense foliage, while ferns have spread along the ground in the downy oak forest, creating a distinctive atmosphere, as shown by **Figure 8** [13].

Since the Forest Laboratory was founded, awareness of climate change has risen sharply, and with it, concerns about how cities can respond to it. When the Cologne city administration is asked about this, it often refers to the Forest Laboratory and



Figure 8.
Downy oak forest with ferns, 2025. © Lohrberg F.

offers guided tours there. Individual tree species that have proved successful, such as the chequer tree (*Sorbus torminalis*), are increasingly being used for reforestation elsewhere.

In the **wilderness forest**, woody plants began to establish themselves through seed germination shortly after agricultural use was abandoned. Initially, pioneer species such as birch (*Betula pendula*) and willows (*Salix* spp.) thrived amidst a lush herbaceous flora. These were soon joined by maples (*Acer pseudoplatanus* and *Acer campestre*) and other species that dispersed seeds from neighboring woodlands. In 2015, small groups of beech trees (*Fagus sylvatica*) – a climax species typical of natural mixed forests in Germany – were also planted to encourage the development of a regionally characteristic forest. By 2025, trees in the wilderness forest had already reached heights exceeding 20 meters. The canopy is now closed, darkening the forest floor and creating a unique microclimate within. While biodiversity in the wilderness forest is comparatively high, accessibility is severely limited due to a lack of paths leading through it. Overall, however, visitors to the laboratory view the wilderness forest as an enriching addition to the landscape.

6. Conclusions

The Cologne Forest Laboratory was very well received by the recreation-seeking public shortly after its establishment. While the harvesting of short rotation plantations initially caused some confusion, this method of utilization has since become accepted on-site. Informing the public – through information boards, guided tours, student interventions, and online platforms such as websites and blogs – has proven to be a crucial success factor for the forest laboratory. In addition, co-producing elements of the laboratory with companies or involving citizens has been beneficial in establishing it. Fifteen years after the initial planting, a forest character

has developed in many areas. Many visitors no longer recall the previous state or planting period; instead, they perceive the forest as something that has always existed. This high level of appreciation for the forest laboratory was further reinforced during the coronavirus pandemic, when urban forests became vital refuges for many people seeking outdoor spaces to relax [13].

Although various forms of forests have been established, the future of the laboratory remains open-ended. For instance, it needs to be determined whether experiments with short rotation plantations should continue or if new forms of urban forests should be explored. The beauty forest does not have fixed objectives regarding which species should be promoted or removed; these decisions will need to be made collaboratively on-site through dialog among the administration and visitors. Furthermore, there is an opportunity to enhance co-production as a powerful tool for creating viable spaces: Can the laboratory encourage visitors – following in students footsteps – to become designers of the forest? Currently, answers to these questions are not available; however, the Cologne Forest Laboratory has proven to be an exceptional place for undertaking such experiments.

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Section 3

Assessing the Trade-offs of Urban Greening Strategies

Microclimatic Effects of Leaf-Turning Tree Species: Improving Local Climatic Conditions in Urban Areas

Judith Carl and Sascha Henninger

Abstract

Urban trees play a vital role in reducing urban heat and improving climate resilience. They cool urban areas by providing shade and evaporating water from their leaves. In this context, the silver lime (*Tilia tomentosa*) has attracted attention due to its ability to turn the silvery underside of its leaves upwards during periods of intense sunlight. This leads to a change in the canopy albedo and a possible decrease in surface temperatures within the crown area. The aim of this study is to assess the potential microclimatic cooling effects of silver lime trees on their immediate environment and to derive evidence-based recommendations for promoting climate resilience in urban areas. In situ measurements are being taken at multiple sites in Kaiserslautern, Germany. The study considers variables such as tree species, developmental stage, and the availability of a directly comparable reference tree.

Keywords: urban microclimate, urban greenery, city trees, urban cooling capacity, silver lime, silver linden, urban heat islands

1. Introduction

The increasing heat stress in urban areas due to climate change poses a significant challenge with far-reaching implications for the health and quality of life of urban populations. Urban heat islands lead to elevated temperatures that pose serious health risks, particularly during heatwaves [1]. Urban heat islands are defined as urbanised areas that experience significantly higher temperatures than their rural surroundings. This phenomenon is primarily caused by human activities and the urban landscape [2–4]. It can have various environmental, energy consumption, public health, and economic repercussions [4, 5]. A comprehensive understanding of the causes, effects, and mitigation strategies of urban heat islands is essential to promote sustainable and resilient urban environments. Therefore, climate adaptation in urban areas is more urgent than ever [6, 7]. According to the IPCC Report, adaptation is defined as “the process of adjusting to actual or expected climate and its effects to moderate harm or take advantage of beneficial opportunities in human

systems. In natural systems, it is defined as the process of adjustment to actual climate and its effects” [6].

There are several strategies that can help reduce the severity of the urban heat island effect. These include the implementation of green infrastructure, such as vegetation and green roofs, to enhance natural cooling processes [8]. Urban greening can affect temperatures through several processes. For example, urban trees can mitigate the effects of urban heat islands by blocking sunlight from reaching the ground, thereby reducing convection, which is a factor in heat island formation. Furthermore, tree canopies increase latent rather than sensible heat fluxes by absorbing sunlight and energy from the environment through evapotranspiration [9]. Additionally, the positive impact of nature on human health and well-being is widely recognised [10]. However, it is important to acknowledge that aesthetic preferences are subjective and can change over time. For example, shading or a dense canopy can be beneficial on hot summer days but less so in cool, humid summers [11].

In addition to their social importance, the demands placed on urban trees are increasing. Traditional species such as the summer lime tree (*Tilia platyphyllos*) and the sycamore maple (*Acer pseudoplatanus*) are increasingly suffering from stresses in urban environments [11–14]. Tree species from southeastern Europe, such as the manna ash (*Fraxinus ornus*) and silver lime (*Tilia tomentosa* “Brabant”), are better equipped to cope with higher levels of heat stress, solar radiation, and drought. This is achieved through lower soil and water potentials, prevention of exceeding the wilting point, increased water use efficiency, lower transpiration rates during the hot season, different leaf morphology, and more vigorous fine root growth [11, 15, 16].

The temperature of trees in urban areas can vary depending on several factors, including species, location, leaf size, and the morphological characteristics of the canopy. At air temperatures of 40°C, the maximum leaf temperature of certain species can increase exponentially by up to 10 K above ambient temperature without irrigation. Furthermore, species that are cooler at 25°C may not necessarily remain so at extreme temperatures. Additionally, species with smaller leaves tend to stay cooler when the ambient temperature is high [17]. Therefore, when selecting trees for urban areas, it is important to consider that not all species have the same cooling effect. Urban tree planting, therefore, needs to be planned carefully in the context of climate change in order to reduce the development of urban heat islands and avoid costs associated with inappropriate species selection.

Acknowledging the increasing role of urban vegetation in regulating climate, this study explores the cooling potential of deciduous tree species as a strategy for adapting to shifting climate conditions in cities. The research specifically examines variations in albedo and surface temperature of *Tilia tomentosa* canopies and evaluates their potential influence on the surrounding environment, with a particular focus on their use as roadside plantings.

2. Urban trees of the future

From 2010 to 2021, the “Urban Green 2021” research project examined 29 tree species to determine their suitability as climate-resilient urban trees. The project aimed to identify species that can withstand heat and drought stress, making them suitable for urban greening in a changing climate.

Southeast European species, such as the silver lime tree and the hop hornbeam (*Ostrya carpinifolia*), were found to control leaf temperatures significantly better than their native sister species, such as the winter lime tree and the hornbeam, during hot spells. They exceeded the critical threshold of 40°C less frequently and for shorter periods, indicating higher heat tolerance. This ability to regulate temperatures was also maintained during successive extreme summers, with the silver lime performing particularly well [18].

The “Urban Green 2021” project recommends the following tree species: silver lime (*Tilia tomentosa*), hop hornbeam (*Ostrya carpinifolia*), field maple (*Acer campestre*), Hungarian oak (*Quercus frainetto*), hazel (*Corylus colurna*), gleditsia (*Gleditsia triacanthos*), and oriental and hackberry trees (*Celtis occidentalis* and *Celtis australis*). It is important to note that the suitability of tree species varies depending on location and regional climatic conditions. The project’s recommendations are therefore regionally specific and take into account the municipalities’ local experience. However, the silver lime and the hop hornbeam are highlighted as particularly suitable across all locations [18].

2.1. *Tilia tomentosa*

Tilia tomentosa, commonly known as the silver lime in the UK and the silver linden in the USA, is a tree native to southeastern Europe. It is drought-resistant and thrives in warm conditions. It is naturally found in regions such as the Balkan Peninsula, north-western Turkey, Hungary, and Romania [19–21]. The climate in the silver lime’s natural habitat shows greater annual temperature variation than the current climate in Rhineland-Palatinate. Higher temperatures are expected in the future, particularly in the Upper Rhine region and river valleys. However, precipitation is expected to remain largely stable. Silver lime is currently considered suitable, but this suitability is expected to increase with rising temperatures by the middle of the century [21].

When exposed to high levels of sunlight, the silver lime tree exhibits unique behaviour by orienting the leaves at the top of its canopy outwards towards the sun. The silver colouring on the underside of the leaves (see **Figure 1**) reduces heat



Figure 1.
Photograph of the leaves of *Tilia tomentosa*, showing the different colours of the upper and lower sides of the leaves [Carl 2023].

absorption and reflects incoming sunlight, which could help cool the tree – a crucial factor in hot weather [22].

The silver lime tree flowers from late July to early August, providing an important source of food for bees and other insects at a time when there is otherwise little available [23]. Therefore, the late flowering period makes the silver lime tree a useful resource for the local insect community. It was once thought that the nectar of the silver lime tree was toxic to insects; however, recent research has disproved this idea. The real reason for the widespread mortality of bumblebees under silver lime trees is food rivalry between insects [11, 24, 25].

3. Materials and methods

Field measurements are currently being conducted in Kaiserslautern (49° 26' 36"N, 7° 46' 08"E), a city in the state of Rhineland-Palatinate in southwestern Germany. Kaiserslautern is characterised as a university and industrial city. It covers an urban area of about 140 km², 87 km² of which is covered by forest [26]. The city's average annual temperature is 10.2°C, with seasonal fluctuations ranging from an average of 1.9°C in January to 19.3°C in July [27]. Notably, the average annual temperature in Kaiserslautern has increased significantly by 2.0 K since the late nineteenth century, particularly in recent decades [28]. Regarding precipitation, the city receives an annual average of 764 mm, with the highest recorded amount being 69 mm in May [29]. These distinctive climatic parameters make Kaiserslautern an ideal location for studying the impact of changing environmental conditions on urban vegetation and microclimatic dynamics.

4. Sampling strategy

This study's sampling strategy focuses on roadside greenery in the urban environment of Kaiserslautern. Streets were carefully selected based on specific criteria to ensure the reliability and representativeness of the data. The primary tree species under investigation are *Tilia tomentosa* and *Tilia tomentosa* "Brabant," which were selected due to their distinctive characteristics and ecological importance in urban environments.

To capture the full spectrum of tree development and its impact on microclimatic effects, the study includes trees at different life stages: youth, maturity, and old age [30]. This approach enables a thorough analysis of how the cooling capacity of the trees may change throughout their lifespan.

A key feature of the sampling strategy is the presence of a direct comparison tree adjacent to each silver lime specimen. This arrangement enables precise comparisons under real-world conditions, as both trees experience similar environmental factors [31]. Such paired sampling enhances the study's ability to isolate the specific effects of silver lime trees on the local microclimate.

The selection criteria also consider various physical characteristics of the trees, such as total height, diameter at breast height, the height of the crown base, and the crown radius. These measurements provide essential context for interpreting the thermal behaviour and cooling capacity of the trees in relation to their size and structure.

The study aims to generate robust data on the microclimatic effects of silver lime trees in urban environments by employing this sampling strategy, which could inform future urban climate resilience strategies.

5. Data collection protocol

This research project examines how trees influence the microclimate within street canyons, focusing particularly on warm summer conditions and extreme heat events, when the cooling effect of trees is most evident. To ensure the collection of relevant data, specific meteorological criteria have been established. Measurements will be conducted exclusively on summer days characterised by low wind speeds (≤ 1.5 m/s), clear to nearly clear skies (degree of cloud cover $\leq 1/8$), and temperatures reaching a minimum threshold of $\geq 25^{\circ}\text{C}$ [30, 31].

In order to fully assess the impact of solar radiation, it is necessary to measure tree canopy temperatures at various times throughout the day. This approach provides valuable insights into how building orientation and shading affect the thermal behaviour of trees. Data collection is scheduled at specific intervals, if possible.

Early morning (07:00–09:00 UTC + 1)

Midday/early afternoon (12:00–15:00 UTC + 1)

Late afternoon/early evening (17:00–19:00 UTC + 1).

These time slots have been chosen to coincide with the researcher's presence, ensuring accurate data collection while avoiding continuous measurement periods that could lead to excessive heat exposure and compromise health and safety requirements [31].

The various measured variables (see next chapter: Equipment and Measurement Techniques) are recorded at 10-minute intervals within the aforementioned time slots.

The study employs a multifaceted approach to understand the thermal behaviour of trees in urban street canyons. Due to the unique characteristics of each tree and measurement site, as well as the variability of weather conditions, the research focuses primarily on intra-tree comparisons to elucidate thermal patterns throughout the day.

6. Equipment and measurement techniques

In situ measurements employ a range of specialised instruments to capture accurate microclimate data around the *Tilia tomentosa* tree and its comparator trees (See **Figure 2** and **3**). The primary equipment includes SwitchBot IP65 Outdoor Sensors to measure air temperature and humidity, a PASCO wireless weather sensor (PS-3209) with GPS to record environmental factors such as wind speed and air temperature, and a TOPDON TC002 thermal imaging camera to measure the surface temperature of tree canopies and surrounding structures.

In this study, a TOPDON TC002 thermal imaging camera is employed to record surface temperatures of both the tree trunk and canopy from three specific angles: the side facing the building façade, as well as the eastern and western canopy exposures [30]. These orientations are strategically selected to detect any potential temperature variations influenced by solar exposure and dominant wind directions.

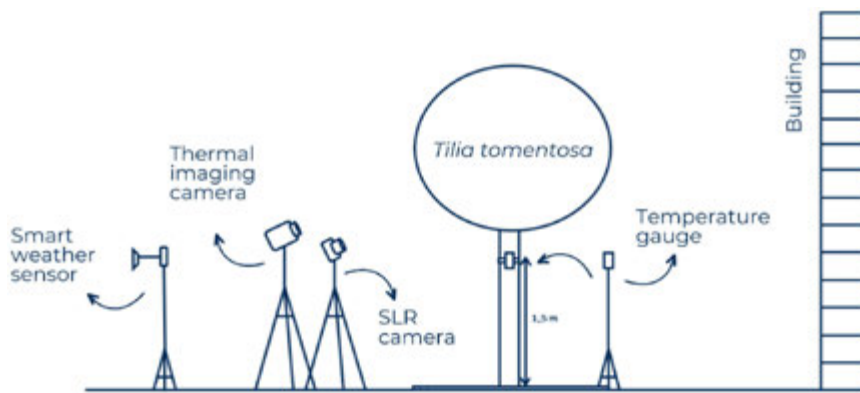


Figure 2.
Outline of the experimental setup, modified from [30].

By examining these perspectives, the research aims to identify potential relationships between the thermal properties of the tree canopy and the adjacent building façade.

Additionally, thermal images of nearby buildings are taken to assess whether the canopy's emitted radiation has any effect on the façades of surrounding buildings. This aspect of the study is a key to evaluating how tree canopy heat dynamics may influence local architecture and contribute to microclimatic conditions. To maintain consistency, all images are captured from a fixed point perpendicular to the wall at each measurement location. Care is taken to prevent or minimise contact between the canopy foliage and the wall surface in order to avoid any potential interference with the temperature readings.

To ensure accuracy, all instruments undergo calibration procedures before each field session. Additionally, the placement of sensors is crucial for capturing the microclimatic effects of the tree. Air temperature measurements are taken at multiple points. The first temperature component is measured just beneath the tree canopy, at a height of 1.5 metres above ground level. This height is chosen as it better reflects conditions experienced at the human level compared to the conventional measurement height of 2 metres [32]. To obtain reliable temperature data, sensors are positioned in shaded locations and protected from direct exposure to sunlight. Additional air temperature measurements are taken from the tree trunk towards the house wall in order to analyse the microclimatic effects in this specific area, particularly with regard to the building façade.

7. Limitations and uncertainties

When conducting research into the impact of silver lime trees on urban microclimates, it is important to recognise and address the limitations and uncertainties of our methodology. These factors influence both the data collection process and the interpretation and generalisability of the findings.

Access and spatial constraints:

One of the primary challenges is restricted access to certain measurement sites. Private properties, the closure of business premises on weekends, and the varying

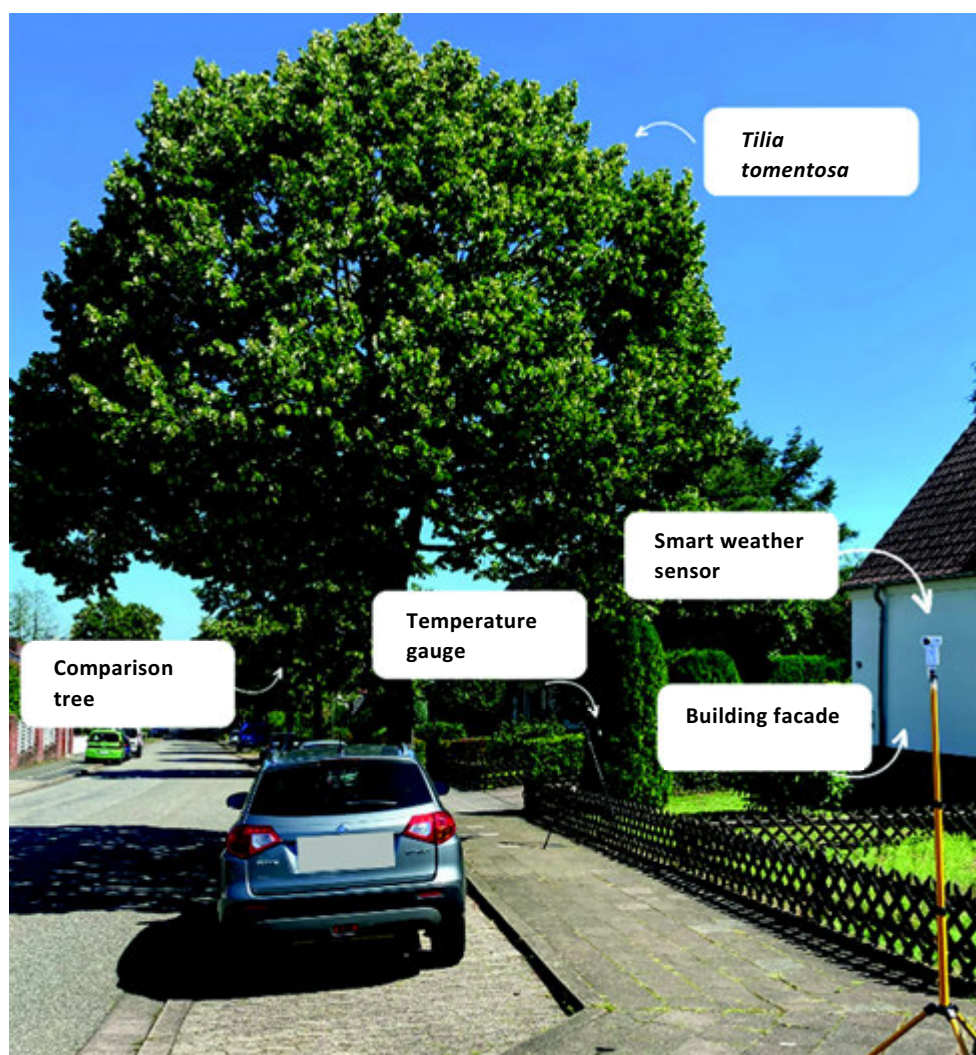


Figure 3.
Insights into the measurements in Buchenlochstraße, Kaiserslautern, on August 11, 2023 [30].

distances from building façades can limit the ability to obtain a comprehensive dataset representing all canopy perspectives. These constraints may introduce a sampling bias, potentially resulting in the underrepresentation of certain urban configurations or tree-building interactions.

Weather variability:

The dynamic nature of urban microclimates makes it difficult to replicate precise weather conditions across different measurement sites and time frames. Factors such as wind patterns, cloud cover, and anthropogenic heat sources can vary considerably, even within small urban areas.

To address this variability, our study primarily focuses on intra-tree comparisons, analysing thermal behaviour within individual trees throughout the day. This approach enables us to control for site-specific factors and isolate

the effects of tree characteristics and immediate surroundings on microclimate modulation.

Scaling and representativeness:

While this study can provide valuable insights into the thermal behaviour of individual trees, it is challenging to scale these findings to larger urban areas. The heterogeneity of urban environments, including variations in building materials, street orientations, and tree species composition, may limit the direct applicability of our results in other contexts.

To address this, we will use a hierarchical modelling approach that incorporates both tree-level and neighbourhood-level variables. This multi-scale analysis will help us understand the effect of individual trees on the aggregate at larger spatial scales and in different urban configurations.

By explicitly acknowledging these limitations and uncertainties, we aim to provide a transparent and robust framework for interpreting our results. Furthermore, this approach enables us to identify areas for future research and methodological improvements, thereby contributing to the ongoing refinement of urban microclimate studies and their applications in urban planning and climate adaptation strategies.

8. Initial results and outlook

As the research project is still ongoing, no final results can be reported yet. However, the following initial trends are emerging: The effect of a potentially cooler leaf surface on the silver lime tree could not be clearly confirmed in the measurements taken so far. Some results indicated a cooler surface temperature compared to a reference tree, while others showed a higher surface temperature. For instance, on 11 August 2023, the silver lime tree had a surface temperature of 31.1°C, whereas the reference tree had a temperature of 30.7°C; however, the silver lime tree showed higher temperatures from 14:00 onwards (see **Figure 4**). On 9 July 2024, the silver lime tree started at 33.0°C, while the comparison tree started at 32.2°C; the temperatures then alternated in subsequent measurements (see **Figure 5**).

In addition, temperature measurements taken from the trunk of the silver lime tree revealed an air temperature that was approximately 0.4 K higher than that recorded for the reference tree. This difference could be attributed to various factors, including microclimate, environmental influences, and parked cars. An initial analysis of the building façades and surface temperatures of the respective tree trunks revealed that direct sunlight had a greater impact on surface temperature than the presence of a silver lime tree. This suggests that external factors such as sun exposure and environmental design play a key role in shaping the microclimate and, consequently, the temperature readings of the building façades.

If the cooling potential of silver lime trees can be reliably quantified, it opens the possibility for simulation using ENVI-met. This software is a robust microclimate modelling tool designed for detailed analysis at the neighbourhood or street scale. It includes visualisation features that help interpret spatial temperature patterns and integrates seamlessly with AI and GIS technologies, allowing the fusion of simulation outputs with geographic data relevant to the study area [33]. The TreePass module within ENVI-met offers an in-depth evaluation of environmental conditions influencing tree growth and sustainability. It takes into account variables such as



Figure 4.
Surface temperature of the canopy of the silver lime tree and a reference tree in Buchenlochstraße on 11 August 2023 [Carl 2024].

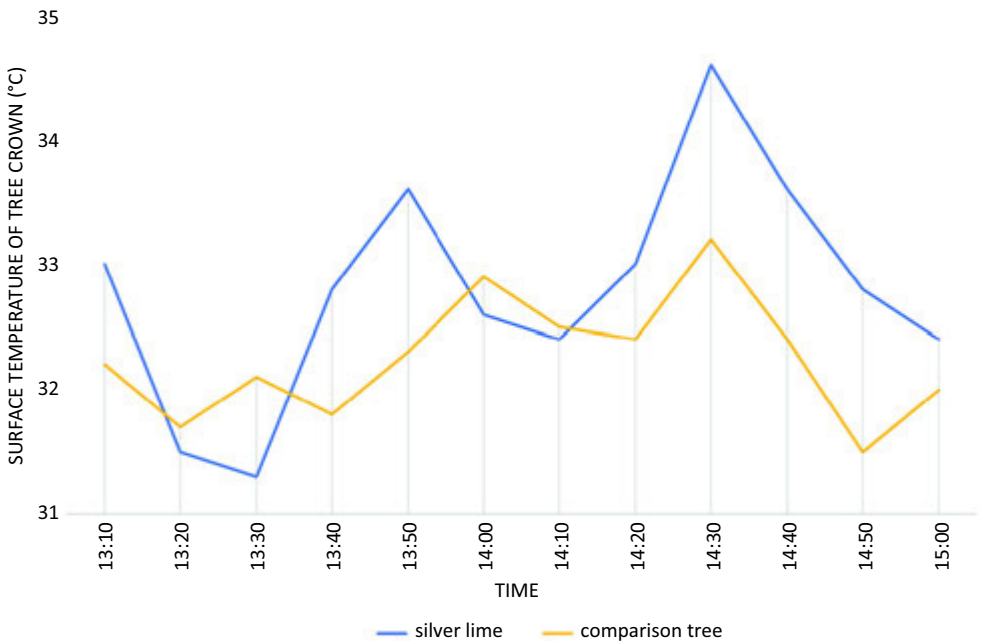


Figure 5.
Surface temperature of the canopy of the silver lime tree and a reference tree in Buchenlochstraße on 09 July 2024 [Carl 2024].

wind exposure, light availability, and mechanical stresses, delivering valuable insights for professionals such as urban planners, arborists, and landscape architects. Such data support evidence-based decisions related to species selection, tree placement, and maintenance practices, ultimately enhancing the resilience and health of urban greenery [34]. The software is capable of modelling scenarios where silver lime trees are introduced more widely or exclusively in urban streetscapes, estimating their impact on local microclimates. It can also be used to compare thermal effects between streets with newly planted silver limes and those with mature or ageing trees. A key goal is to determine whether younger silver lime trees, due to their leaf rotation mechanism, offer more effective cooling than older specimens. Furthermore, simulations can estimate the time required for newly planted silver limes to match the cooling performance of established street trees. ENVI-met's capabilities offer a valuable toolset for exploring how silver lime trees influence urban climates and for guiding climate-responsive urban greening strategies.

Ongoing research on *Tilia tomentosa* in urban environments could significantly influence sustainable urban planning and design. This study aims to provide evidence-based recommendations for urban greening initiatives, focusing on enhancing public spaces and selecting suitable vegetation.

Key areas for future investigation include evaluating the local climate impacts of silver lime trees in order to determine the most suitable locations for them in urban areas. Understanding how silver lime trees interact with green-blue infrastructure could improve urban ecosystem services and resilience to climate change. Developing strategies for the gradual replacement of trees and the integration of young saplings can help to ensure urban canopy coverage. Furthermore, it is essential to evaluate the costs, benefits, and social implications of integrating silver lime trees into urban landscapes.

It is also important to explore how silver lime trees can enhance urban resilience in response to changing environmental conditions. Addressing these research areas enables urban planners and landscape architects to make informed decisions that enhance the liveability, sustainability, and climate resilience of cities [31]. This comprehensive approach to studying silver lime trees in an urban context reflects the complex nature of urban ecosystems and the need for a holistic approach to urban planning.

9. Conclusion(s)

In the context of mounting climate challenges, urban areas have taken on a key role in leading the way with strategies to mitigate the effects of climate change. Urban planners and policymakers are spearheading the implementation of initiatives that enhance the resilience of current and future urban landscapes.

Municipal authorities are leading the way in implementing forward-thinking urban planning strategies to address climate adaptation. These strategies encompass updating building codes to enhance structural resilience against climate-related challenges, integrating green and blue infrastructure to reduce the impact of severe weather, and developing focused initiatives to safeguard at-risk communities and essential infrastructure. These actions are crucial for making cities more resilient and sustainable in the long term as they contend with the effects of a changing climate.

Although urban areas are particularly vulnerable to the effects of climate change, effective adaptation strategies are a cost-effective solution. Long-term adaptation efforts are more economically viable than taking no action at all.

Strategic urban greening is a vital component of climate adaptation in cities. This involves meticulous planning, species selection, and assessment of species-specific cooling effects and adaptability to local climate conditions, as well as consideration of long-term maintenance requirements. By carefully selecting climate-resilient tree species, cities can maximise the benefits of urban greening while enhancing their climate resilience. The benefits extend beyond mere adaptation to include improved microclimates, enhanced water management, better air quality, increased biodiversity, and greater urban vibrancy.

Effective climate adaptation requires existing policies to be aligned with climate-friendly objectives and climate-resilient investments to be ensured. This involves integrating adaptation measures into current policies to promote policy coherence and synergy while minimising counterproductive actions. At the municipal level, a comprehensive, multidisciplinary approach is essential. This includes fostering collaboration with neighbouring municipalities, regions, and countries to reinforce adaptation initiatives and pave the way for a more resilient urban future.

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Data availability statement

The full datasets presented in this article are not readily available because the study is still ongoing.

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Chapter 8

The Allergenic Potential of the Plants

Francesca Marinangeli and Loretta Giuseppina Pace

Abstract

The allergenic potential of pollen emitted by plants is one of the factors that need the most attention in urban greening because it has a high impact on the quality of air and the health of citizens. The most crucial problem is the lack of knowledge about the allergenic capacity intrinsic to cultivated or wild plants. This treatment of the allergenic potential of plants becomes a valuable tool for management and evaluation by allergologists or general practitioners. The result of this study is the allergenic potential of plants assessed from the most up-to-date literature references. This chapter aimed to focus on the allergenic potential of plants and other harmful or positive interactions between plants and human respiratory health, to treat and discuss the criteria most used in international literature for value and to show its value for the most frequent plants (botanical families, genera, species, varieties) in urban parks, school areas, sports areas, wild spaces, and forests near urban cities in some world areas. This is also a risk mitigation measure in planning urban spaces and green infrastructures for people affected by pollinosis and applying sustainable development goals for sustainable cities, good health, and well-being.

Keywords: allergenic plants, allergenic pollen, assessment of allergenic potential, airborne pollen, pollinosis, urban parks, green areas, invasive plants, climate change

1. Introduction

Shortly after the emerged lands were conquered, plants evolved into the appearance of superior plants (higher plants) that have cones or flowers with male and female parts in the same individual or distinct individuals. Pollen is released by the male organs of higher plants on the terrestrial surface to find the female ones for breeding, cross the genetic material, and thereby increase biodiversity and resilience to environmental impacts. Pollen emissions (PE) from plants can harm human health, particularly in respiratory diseases and in sensitive places such as schools, hospitals, or sports areas (**Figure 1**). Indeed, contact of pollen granules with the mucosae or eyes can cause allergic reactions or sensitisation in the human population [1]. Allergic respiratory diseases are serious public health challenges in many countries and regions. Asthma affects more than 350 million people worldwide and is



Figure 1. Wind-dispersed pollen cloud emitted from *Cupressus* in a schoolyard in Perugia, Italy. (photo by Francesca Marinangeli).

the most common chronic disease in children, affecting at least 30 million children and young adults in Europe [2]. Not all types of pollen cause allergies in humans. There are several allergenic plants with varying grades or intensities, as well as non-allergenic plants. Studies on this topic are relatively recent, focusing on a few more impactful plants, and are not yet very widespread. The meaning and evaluation of allergenicity are much discussed in the scientific world. The interpretation of allergenicity can be considered in two main ways [3]: In botanical significance, a plant is highly allergenic when its pollen triggers very strong allergenic symptoms in some individuals, or in epidemiological significance, when many people suffer from pollen emitted by a plant. In Europe, one of the most vulnerable regions for air pollution effects on respiratory health [4], 35% of the population suffers from allergies to the Poaceae family, and during the last few decades, the prevalence of pollen allergies has increased [5], as has been observed in other continents (Africa, Asia, America). Pollen grains can also travel across countries or seas far from their emission source. In some cases (eg, in Michigan, USA, for *Ambrosia artemisiifolia*), scientists use satellite images to predict pollen diffusion or concentration [6]. It is possible to study the phenology of airborne pollen, including timing and duration,

and determine the direction and source area of PE [7, 8]. Data on the presence and prevalence of allergenic airborne pollen, obtained from both aerobiological studies and allergological investigations, make it possible to design pollen calendars with the approximate flowering periods of plants in the sampling area [5, 9]. The pollen map is changing, as shown by aerobiological and allergological studies by the same author in Europe, due to cultural factors (green area planning), globalisation and colonisation by alien plants, and climate change, which cause weather extremes, thunderstorms, windstorms, and increasing episodes of long-range transport of allergenic pollens or subpollen particles [10]. Therefore, it is essential to know and consider, also in diagnostics, the allergenic potential of a plant, even if it lives in other places (alien species). Concerning climate change, many studies carried out in the last decades have shown that the pollen season for taxa flowering in winter and spring in temperate regions has tended to occur earlier, probably due to the continuous rise in temperature. The flowering of one of the most allergenic families, the grass family, has been observed in Central Italy in a 33-year study [11]. Poaceae pollen is currently the leading airborne biological pollutant and the chief cause of pollen allergy worldwide [12]. It is also essential to consider the interaction between pollen and air pollutants to gain new insights into the mechanisms of respiratory allergic diseases, as specific weather conditions can modify pollen's allergenic potential [4]. The additional influence of urban pollution may prompt a more severe immunological response [12]. Some plants can cause adverse reactions even by ingesting fruits or other parts. There are also cross-reactions between common allergens in Mediterranean plants and commonly consumed fruits [13]. However, plants are not only hostile to the human respiratory system: They produce oxygen, purify the air with their leaves, and some plants can positively affect the respiratory system due to balsamic substances. Clean air is essential for our health, and sustainable development goals aim to create healthier cities. It is fundamental to spread knowledge in botanical allergology and correctly plan green areas.

2. Airborne pollen and allergy

Pollen is the male gametophyte of spermatophytes, higher plants that reproduce sexually, and its main function is fertilisation. Spermatophytes are subdivided into angiosperms and gymnosperms depending on whether or not the seed is protected by an ovary [14]. Allergy refers to the spontaneous and exaggerated reactivity of the body of a sensitive individual to substances that are harmless to the rest of the population [5]. The etiologic agent responsible for pollinosis is pollen, particularly its protein and glycoprotein components, both internal and membrane. Protein, lipid, and polysaccharide molecules, various enzymes, and microorganisms are found in pollen. Their interaction influences the corresponding cell receptors, causing inflammation [15]. Once pollen comes into contact with the nasal and/or oral mucous membranes, it undergoes initial lysis, which releases the allergenic protein fractions that can then act locally and at the level of the small airways. Once inhaled, pollen grains are attacked by enzymes in mucous secretions; the wall is dissolved, and allergenic molecules are released. The characteristic of the allergenic molecules present in the pollen granule is that they interact with the immune system of sensitive individuals, triggering allergic reactions. On the outside of the pollen wall (exine) are proteins and glycoproteins that have the critical function of

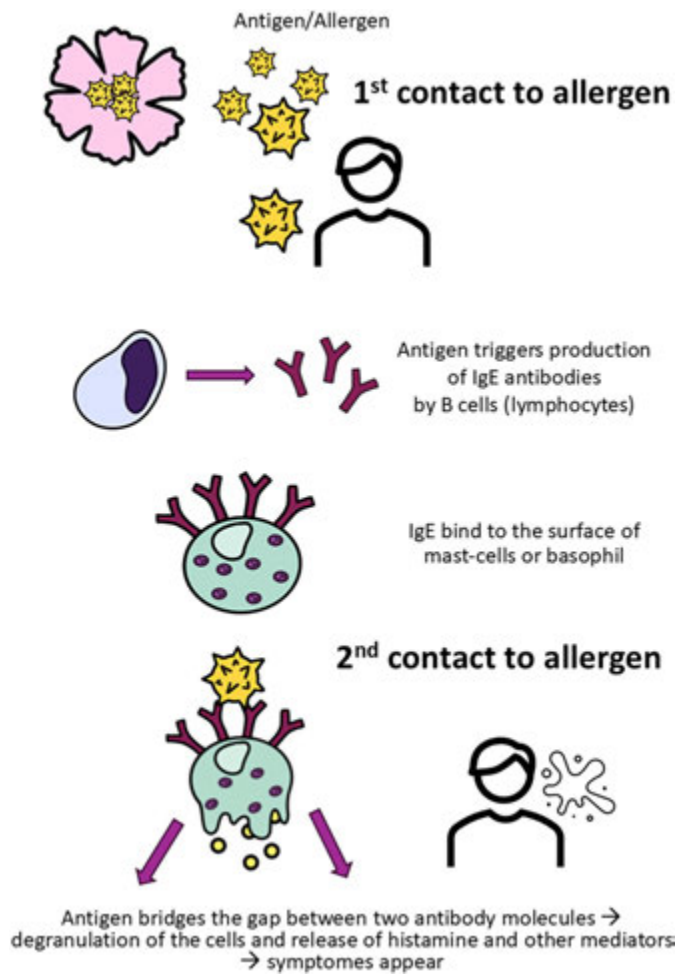


Figure 2.
The mechanism of allergic reaction: allergen (antigen)–antibody.

species-specific recognition. At first, it was thought that pollen allergens were only those located on the exine; later, it was ascertained that most of them are contained within the granule and that they escape from the openings (pores, colpi, colours) very quickly once in contact with a moist surface. Pollen allergy is a Type 1 hypersensitivity (IgE-immediate) reaction to specific allergens [16]. The allergic reaction consists of producing IgE antibodies in response to an antigen (pollen) and binding to receptors on mast cells (immune system cells) (**Figure 2**). On second contact, the allergen binds to IgE, which in turn binds to mast cells that release numerous chemical mediators (histamine, proteases, acid hydrolases, and proteoglycans) that, when released, result in allergy symptoms. Pollen grains can have multiple allergens. ‘Major allergens’ are defined as those that are capable of causing the production of specific IgE in more than 50% of patients allergic to that pollen. Meanwhile, ‘minor allergens’ are defined as those that cause IgE production in a lower percentage of patients [12, 17].

2.1 Pollination strategies

Pollination is the process that allows the pollen granule produced by the anthers of one flower to reach the stigma. Pollination strategies may be anemophilous (wind pollination), entomophilous (insect pollination), and amphiphilous (mixed pollination) (**Figure 3**). The oldest angiosperms are believed to be endogamous, that is, pollinated by the wind. Around 100 million years ago, as insects spread, plants gradually switched to entomogamous pollination. There was thus a continuous coevolution between plants and pollinating insects that led to a progressive transformation both morphologically, especially of the flowers and the insects' mouthparts, and biochemically, with the synthesis of chemical attractant compounds (pigments, odours, sugary substances) [18–20]. In some genera of Asteraceae, such as *Ambrosia* and *Artemisia*, environmental pressure has shifted from entomogamy to anemogamy. This is how plants respond to environments characterised by drought, sun, and wind, to avoid pollinating many flowers. In many trees in temperate climates, such as the hazel, flowers bloom early in the spring awakening or even in the middle of winter. The leaves will open after fertilisation has taken place: This is to encourage cross-pollination. Anemogamous plants have special characteristics: high pollen production, although the wind causes a huge loss of pollen, and the lack of all those parts of the flowers that are superfluous, such as brightly coloured petals. Although these interactions are frequently disregarded, pollinators visit wind-pollinated plants to gather pollen or for materials and nest locations [21]. Wind-pollinated flowers do not produce nectaries, have dull colours and

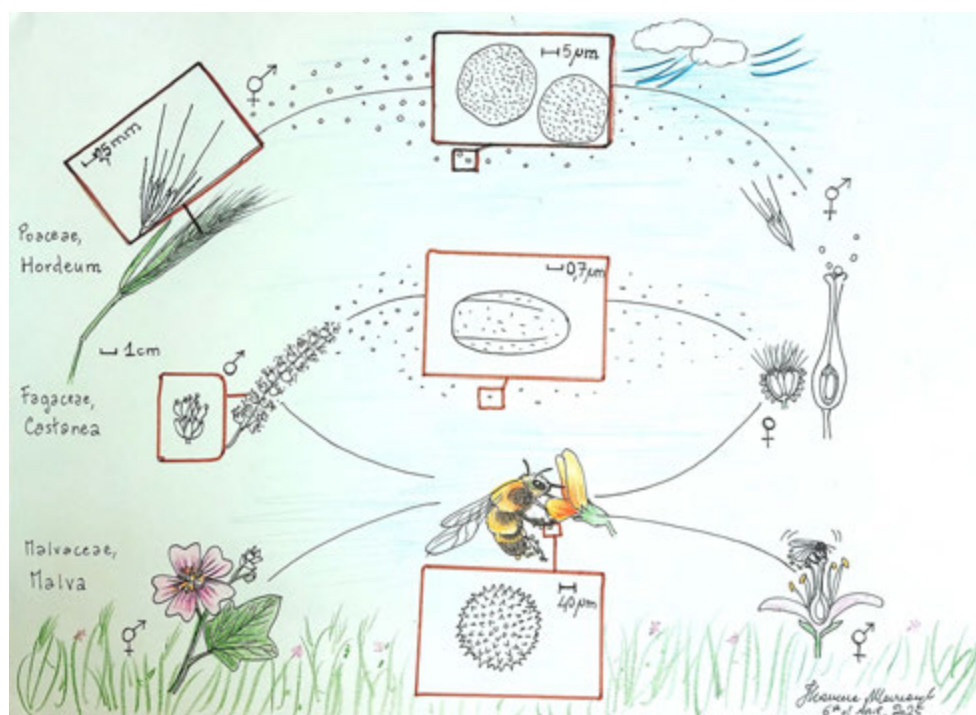


Figure 3.
 Anemophilous, amphiphilous, and entomophilous pollination schemes in *Hordeum* (Poaceae family), *Castanea* (Fagaceae family), and *Malva* (Malvaceae family) (illustration by Francesca Marinangeli).

are generally odourless. In them, the pollen surface is smooth or slightly grained (eg, Poaceae: *Hordeum* sp., *Lolium* sp., Cupressaceae: *Cupressus* sp., *Juniperus* sp.), and the shape is sufficiently aerodynamic to be carried over considerable distances. In some cases, the pollen grains have aerodynamic air pockets (Pinaceae: *Pinus* sp.) or are very small (Urticaceae: *Parietaria* sp., Fagaceae: *Castanea sativa*). In contrast, non-allergenic plants have showy, fragrant flowers (Malvaceae: *Malva* sp.). Poorly aerodynamic pollen sometimes has specific sculptures in chains or microchips. In addition, many pollen grains are covered with a viscous liquid, the 'pollenkitt', which plays an important role in pollen dispersal and adhesion (*Betula*, *Crocus* genera) [14].

2.2 Spread of anemophilous pollen

The relationship between wind and pollen release, concentration, and dispersion in the atmosphere is fundamental in aerobiology. For example, see [22–26]. The pollen dispersion in the atmosphere forms the so-called biological aerosol, which can be an etiological cause of disease [27, 28]. The aerosol is a biphasic system (a heterogeneous mixture of two or more components) that can be inhaled and is represented by a continuous gaseous phase (oxygen, nitrogen, etc.) and a discontinuous phase of individual particles with a diameter between 0.001 μm and 100 μm . The entire atmosphere can be defined as an immense biological aerosol containing the dispersion of viable and nonviable biological particles. The troposphere is the aeriform belt of the Earth's atmosphere in direct contact with the Earth's surface. It varies in thickness depending on latitude (at the poles, it is only 8 km thick, while at the equator, it reaches 16–20 km). The release of pollen into the atmosphere occurs when the particles manage to enter the turbulent layer of the troposphere. The release mechanism is passive in that it requires the action of external agents such as wind and rain [29, 30]. Pollen in environmental conditions of high relative humidity tends not to be released. The greater the wind speed, the easier it is for pollen grains to break free from their substrate. The pathway of the pollen is, therefore, due to physical forces acting on the pollen granule, such as friction with air molecules, the force of gravity, and gas displacements in the atmosphere. In addition, an important factor is the size of the pollen grain, as it is based on this that one can assess the tendency of the particles to deviate from their path and thus characterise their aerodynamics. Comparing the pollen grain to a sphere in laminar motion concerning a fluid, the viscous friction force it is subjected to is described by Stokes' law [31]. It follows from the equation that the smaller the particle size, the lower the settling velocity. The average diameter of pollen is about 25 microns, and their falling speed, under absolutely stable atmospheric conditions, according to Stokes' law, should be 7.5 cm/sec. The Earth's atmosphere has also been described as an ocean of agitated air; in fact, it comprises several heterogeneous layers, resulting in alternating layers of warm and cold, moving air that determines what is known as atmospheric turbulence. Long-distance transport can also be favoured during violent thunderstorms with vertical air movement [32]. In 80% of cases, pollen is deposited on the ground a few meters from its source. However, the distance travelled by pollen can vary depending on the height of the plant producing it and the wind speed [33, 34]. For long-distance transport (even hundreds of kilometres), favourable conditions are turbulent air conditions that drag the pollen upwards and stable air conditions for prolonged transport at high altitudes [35, 36]. At night, the decrease in ground temperature reduces the possibility of

pollen passing from the bottom to the top. During the day, the particles will be subject to convective motions that depend on the heating and cooling of the ground. During the sunny hours, the air close to the ground warms up more, and being less dense than the cold air, it tends to rise and drag the particles even to high altitudes. Here, the atmosphere is thinner, so the viscosity of the air decreases, allowing the particles to travel with greater stability. The ideal conditions for long-distance transport are turbulent initially to allow the pollen grains to be released, and subsequently stable conditions for prolonged transport.

2.3 Pollen seasons

Flowering and pollen transport are strongly influenced by environmental conditions [37]. The flowering phase is related to the number of daylight hours in the day and the thermal conditions of the period. The same species does not flower everywhere at the same time; it will generally flower earlier in the southernmost distribution areas and at lower altitudes. Flowering will be delayed or brought forwards depending on the climate and weather pattern of the distribution area. The start of pollination of each plant species depends on the botanical species, geographical area, altitude, and weather pattern of the growing season [38, 39]. Plants release their pollen only when the weather is dry and relatively warm. Pollen concentration varies during the day, usually being highest during the hottest hours of the day. During periods of good weather, airborne pollen is constantly present. Even during the night, there may be pollen in the air unless there has been heavy rainfall during the day. After heavy rain, allergy sufferers experience relief. After a rain shower, the increased humidity in the air rehydrates the pollen, which becomes more strongly allergenic. However, pollen broken up by rain can be just as harmful because it reaches the deep airways. Poaceae pollen decreases significantly on rainy days, while it is estimated that a birch tree can start releasing pollen into the air as early as an hour after it has stopped raining. The allergy-causing molecules present in pollen are proteins in nature and are characteristic of being released during the hydration of the pollen granule [40, 41]. These molecules can interact with the immune system of sensitive individuals, thus triggering allergic reactions. Considering the different abilities of each pollen to trigger an allergic response and the significant or minor allergens present, reference concentrations are indicated as low, medium, and high. In **Table 1**, the values and the colours denote standard concentration classes used in aerobiology: absent (white), low (yellow), medium (orange), and high (red). The assessment refers to the amount of pollen of the various anemophilous taxa in the air. It does not indicate the ‘threshold’ pollen concentrations triggering an allergic reaction. Ranges of pollen concentrations refer to the values reported in the Italian Society of Aerobiology Medicine Environment (formerly the Italian Association of Aerobiology) [42].

2.4 Aerobiological monitoring and networks

Aerobiology is a discipline that studies pollen and other particles dispersed in the atmosphere, their origin, their diffusion, and the effects they produce on the environment [43]. Pollen is collected using a volumetric Hirst-type trap to count pollen (**Figure 4**) [44, 45]. Aerobiology provides various contributions in different fields, such as medicine, specifically allergology, environmental science, plant

Family	Genera more representative	Null/non relevant	Low	Medium	High
Aceraceae	<i>Acer</i>	≤ 0.9	1–19.9	20–39.9	≥ 40
Amaranthaceae/Chenopodiaceae	<i>Amaranthus</i> , <i>Chenopodium</i>	0	0.1–4.9	5–24.9	≥ 25
Asteraceae (sin. Compositae)	<i>Ambrosia</i> , <i>Artemisia</i>	0	0.1–4.9	5–24.9	≥ 25
Betulaceae/ Corylaceae	<i>Alnus</i> , <i>Betula</i>	≤ 0.5	0.6–15.9	16–49.9	≥ 50
	<i>Carpinus</i> , <i>Corylus</i> , <i>Ostrya</i>	≤ 0.5	0.6–15.9	16–49.9	≥ 50
Cupressaceae/ Taxaceae	<i>Cupressus</i> , <i>Thuja</i>	≤ 3.9	4–29.9	30–89.9	≥ 90
	<i>Juniperus</i>	≤ 3.9	4–29.9	30–89.9	≥ 90
	<i>Chamaecyparis</i>	≤ 3.9	4–29.9	30–89.9	≥ 90
Cyperaceae	<i>Cyperus</i> , <i>Carex</i>	≤ 0.9	0.1–4.9	5–9.9	≥ 10
Euphorbiaceae	<i>Euphorbia</i>	≤ 0.9	0.1–4.9	5–9.9	≥ 10
Fagaceae	<i>Castanea</i> , <i>Fagus</i> , <i>Quercus</i>	≤ 0.9	1–19.9	20–39.9	≥ 40
Poaceae (sin Gramineae)	<i>Avena</i> , <i>Dactylis</i> , <i>Cortaderia</i> , <i>Calamagrostis</i> , <i>Miscanthus</i> , etc.	≤ 0.5	0.6–9.9	10–29.9	≥ 30
Moraceae	<i>Broussonetia</i>	≤ 2	2–19.9	20–69.9	≥ 70
	<i>Morus</i>	≤ 2	2–19.9	20–69.9	≥ 70
Myrtaceae	<i>Eucalyptus</i>	≤ 0.9	0.1–4.9	5–29.9	≥ 30
Oleaceae	<i>Fraxinus</i> , <i>Olea</i>	≤ 0.5	0.6–4.9	5–24.9	≥ 25
	<i>Ligustrum</i>	≤ 0.5	0.6–4.9	5–24.9	≥ 25
Pinaceae	<i>Pinus</i>	≤ 0.9	1–14.9	15–49.9	≥ 50
Plantaginaceae	<i>Plantago</i>	≤ 0.9	1–0.4	0.5–1.9	≥ 2
Platanaceae	<i>Platanus</i>	≤ 0.9	1–19.9	20–39.9	≥ 40
Polygonaceae	<i>Rumex</i> , <i>Polygonum</i>	≤ 0.9	0.1–4.9	5–9.9	≥ 10
Salicaceae	<i>Populus</i> , <i>Salix</i>	≤ 0.9	1–19.9	20–39.9	≥ 40
Ulmaceae	<i>Ulmus</i>	≤ 0.9	1–19.9	20–39.9	≥ 40
Urticaceae	<i>Parietaria</i> , <i>Urtica</i>	≤ 0.19	2–19.9	20–69.9	≥ 70

Table 1.
Pollen abundance classes (granules/m³ air/day) [42], mod.

science, meteorology, phenology, and climate change. Many countries must create an aerobiological monitoring network for pollen allergy sufferers. The network aims to offer a service that can provide real-time trends of allergenic pollen concentrations so users can resort to vaccines before rhinitis and asthma attacks occur. There are several monitoring networks around the globe. In 2020, 879 active pollen monitoring stations were found [46]. Pollen monitoring coverage is biased toward the Northern Hemisphere (mainly in Central America, Europe, and Asia); Europe has more than 500 spore traps, among which we cite, for example: ‘Réseau National de Surveillance Aérobiologique’ (RNSA), France; ‘Red Española de Aerobiología’ (REA), Spain; ‘Rede Portuguesa de Aerobiologia’ (RPA), Portugal; ‘Rete Italiana Monitoraggio Aerobiologico’ (R.I.M.A.®) and POLLnet, Italy; ‘National Pollen and Aerobiology Research Unit’ (NPARU), UK; and ‘European Aeroallergen Network’ (EAS),

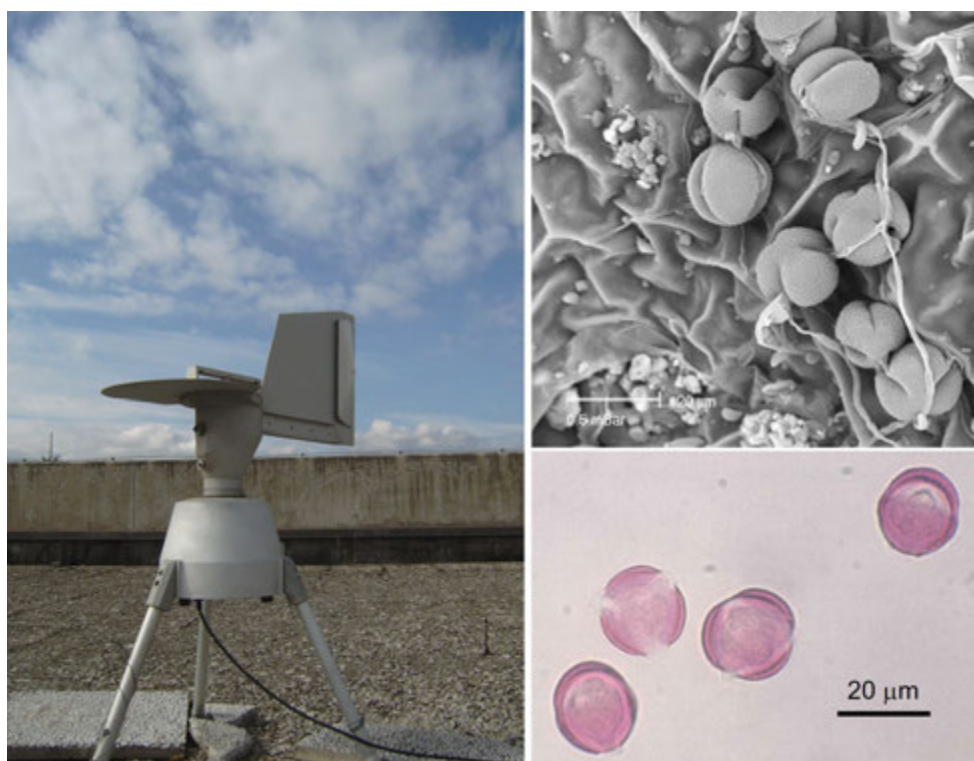


Figure 4.
 Volumetric Hirst-type trap. Pollens of the genus *Artemisia* observed by scanning electron microscope (above) and optical microscope (below) (photo by L. Pace).

Austria. MedAeronet is a network linking Croatia, France, Italy, Spain, and Turkey [47]. Some spore traps are in Argentina and Australia. They are present almost only in South Africa, where the most extended annual monitoring exists for Cape Town (about 20 years), but the data series were not continuous. In 2019, a new network, the interdisciplinary network (SAPNET), was launched to monitor weekly variations of aerospora and provide online data [48] to establish regional pollen calendars [46].

3. The allergenic potential of the plants

3.1 Definition

Every plant known to provoke an allergic reaction in humans would be considered allergenic [3]. The plant's allergenic potential (also called ap) could be defined as 'the possibility of a plant triggering an allergy reaction in sensitive people'. The criteria to define an allergenic plant are four and are named Thommen's postulates in [3]:

- I. The presence of an excitant (allergens) for hay fever and/or asthma in pollen grains is necessary.

II. Pollen grains have to be light and small enough to be carried by the wind for considerable distances.

III. Pollen grains must be wind-borne.

IV. Pollen grains should be produced in large quantities.

Some authors [3, 49] have proposed the addition of two other factors:

V. The plant mother must be abundantly distributed within a territory.

VI. The length of the pollen season defines the allergy impact.

In a multidisciplinary approach, other factors should be considered, as shown in a study conducted in Porto, Portugal (2005–2007) [50]:

VII. The population reactivity measurement (deducible from hospital admissions data for asthma or dyspnoea).

VIII. Immunochemical data (specific IgE to pollen extracts) about contemporary pollen dispersion (detectable by volumetric trap, microscope, or gel electrophoresis analysis).

For an allergic reaction, an interaction between an antigen (from a plant individual) and an antibody (in a human individual) is necessary. The allergenicity of plants (pollen, fruits, other parts) depends on several factors. Plant proteins can cause allergic diseases in susceptible people through immune-mediated reactions; for example, see [51]. Proteins, the antigens, and the essential building blocks of the plant organism may be contained in pollen granules, leaves, stems, fruits, roots, and all other parts.

3.2 Factors on which the allergenic potential depends

The expression of ap depends on several factors, of which the main ones are reported in this paragraph.

3.2.1 Immunogenicity ‘Notes on the immunogenicity of pollen’

The presence of allergens in plants is defined as an immunogenicity factor important for the allergenic potential (ap) [3]. Allergens are defined by the World Health Organization/International Union of Immunological Societies (WHO/IUIS) in an official allergen nomenclature [52], which includes the taxon name (family, genus, species, variety) on the official website [53]. The website provides a database with all the proteins, in a standardised name, contained in various parts of plants that cause IgE-mediated (atopic) reactions in humans. The allergen nomenclature was created in 1986 in the USA [54] for highly purified, well-characterised allergens and nonpurified or partially purified allergenic extracts. For example, ‘*Lol p I*’ refers to *Lolium perenne* allergen number one. The nomenclature criteria were revised in 1994 [55] with the inclusion of allergen genes, mRNAs, cDNAs, and recombinant and

synthetic peptides of allergenic interest. Subsequent revisions occurred in 1995–1996 [56], 2018 [57], and 2019 [52]. In the database, research can be limited to all allergens, such as food, airborne, contact, injection, and unknown allergens. In this section, only pollen allergens were addressed. The latest revision [58] includes 55 new allergens found in plants, defined between 2019 and 2021 (one due to contact, 38 for respiratory contact, and 16 via food), all tested on human patients. The respiratory allergens derived from plants include: *Artemisia vulgaris* (a profilin named Amb t 8, a protein found only in Asteraceae pollen), *A. absinthium*, *A. annua*, *A. argyi*, *A. californica*, *A. capillaris*, *A. frigida*, *A. gmelinii*, *A. ludoviciana*, *A. lavandulifolia*, *A. sieversiana*, *A. tridentata* (defensin-polypyrroline-linked protein (DPLP) and/or PR-1 proteins); *Cannabis sativa* (common name marijuana), which contains proteins such as Can s 2 (a profilin) and Can s 4 (oxygen-evolving enhancer protein and PR-10 homologue), causing immediate symptoms upon exposure; *Cryptomeria japonica* (reaction in cypress pollen-sensitised subjects); *Cupressus sempervirens* (Cup s 7, a GRP protein); *Juniperus ashei* (a GRP protein, causing reactions in subjects with peach allergy and subsequent cypress pollinosis); *Morus alba*, from the Rosaceae family (a cobalamin-independent methionine synthase protein); *Phleum pratense*, a grass (expansin-like protein), and an Asian grass, *Zoysia matrella* (a pollen expansin useful for stigma penetration); Tree pollen from *Populus nigra* (profilin), *Quercus acutissima* (PR-10 and profilin), *Quercus ilex* (PR-10), and *Quercus mongolica* (PR-10). The PR-10 proteins from birch (*Betula* genus) and related trees of the Betulaceae and Fagaceae families are cross-reactive and are major causes of allergic rhinitis. The GRP proteins (snakins, gibberellin-regulated proteins) interact with plant hormones and are involved in cross-reactions with peach (*Prunus persica*), plum (*Prunus domestica*), pomegranate (*Punica granatum*), or citrus fruits in individuals with Cupressaceae pollen allergy [58]. A list of the main allergenic plants and the presence of allergens in the IUIS database can be found in Section 5.1 on biodiversity and allergenic potential.

For pollen allergens, another library is published [59]. This collection was developed as another resource for allergy sufferers to aid in the identification and management of their allergies. It contains more than 1,100 species of plants, with information about their allergenicity, native country, life cycle (perennial, annual), description, if it is evergreen or deciduous, geographical distribution, seasonal pollination, maps of the countries where the plants are available and photographs to identify or recognise them. Searching a plant/genus for a common name, Latin name, or by alphabet is possible. An allergenic plant is described, if allergenic, in three classes: mild allergen, moderate allergen, and severe allergen (f.e. *Cupressus*).

The Allergome database [60] was developed and released on the web in 2003 by public and private institutions as part of a project to collect data on allergen proteins. It is possible to find a group of allergen proteins (eg, profilin) or a specific allergen linked to the sources citing it. More than 6,000 Allergome monographs have been published. In the latest update, 2,554 allergen sources were included in this library. The allergens are linked to the species containing them, with both common and Latin names.

3.2.2 Morphology, pollination strategy, and pollen production

Allergenic potential depends on the pollination strategy (mainly by wind, insects, or both in amphiphilous taxa), which is more important than morphology [3] and floral architecture [51]. In dioecious species (with separate female and male

individuals), only male individuals can produce and release allergenic pollen, while female individuals have zero potential [61]. Low ap is also found in cleistogamous (closed nuptial) flowers or ornamental cultivars, such as double-flowered cultivars, whose pollen will perform self-fertilisation [3]. The amount of daily airborne pollen is recorded at monitoring stations using pollen traps. Pollen-release intensity in wind-pollinated species is linked to plant size (trees and shrubs) and ground cover (herbs); greater crown volume means greater pollen release since larger species tend to have more branches, blossoms, and stamens per unit of surface area [62]. The amount of pollen released into the air is directly proportional to the number of individuals of a single species in any given area.

3.2.3 Life cycle and length of flowering phase

The plant's life cycle [63] is very important in determining the ap. Perennial species, in general, produce more pollen than annual species, even though annual species can blossom again during the year in response to rising air temperatures caused by climate change. The phenology of the plant, as well as the climate and the specific weather trends of the seasons in a year, is very important in defining ap; in particular, the length of the anthesis period, also referred to as the principal pollination period (PPP), is defined in [49].

3.2.4 Distribution of plants in a territory

The chorological type (or chorotype) defines plants' genetic origin, spatial distribution, and ability to adapt to climate. This distribution indicates the adaptation of a taxon to the environment, soil, and climate, and the reaction to their changes depends on the chorotype. For example, increasing air temperature can favour Australian plants but not Panboreal plants. Chorotypes may directly or indirectly influence the adaptive potential (ap) of plants [64, 65]. The distribution of plants is also determined by other important factors such as the germination capacity of seeds, resilience to climate change, the strength of the plant population, and the invasiveness of habitats by alien species [66].

3.2.5 Abiotic factors

The extrinsic or abiotic factors on which the allergenic potential of plants depends are air temperature [67], air moisture, prevailing winds (determining the geographic distribution of airborne allergens), seasonal weather trends, rainfall, thunderstorm frequency (directly provoking severe asthma in some subjects) [68], climate change in general, length of day and night (influencing PE) [69], altitude and latitude (influencing the start and end dates of flowering), and geographical morphology, such as the presence of mountain ranges, lakes, or seas (influencing the diffusion of airborne pollen by wind over long distances). The increase in the atmosphere's carbon dioxide concentration and air temperature [3, 11, 49] has an impact on sources of airborne allergens and, consequently, on allergen exposure of the population and the manifestation of allergic respiratory diseases, such as allergic asthma and allergic rhinitis [69].

3.3 The assessment of the allergenic potential

The ap can be classified into several classes. Different plant taxa (family, genus, species, botanical varieties, or cultivars) can cause allergic symptoms ranging from non-allergenic to highly allergenic grades. The allergenic potential of the plants was evaluated by considering the characteristics of the plant and the aspects of pollination by spontaneous or cultivated flora. It can be assessed as a two-form qualitative value (yes/no) or through indexes in graded systems [3]. On a timescale, seven methods of evaluation, intrinsic or extrinsic to plant characteristics, qualitative/estimative or graded, are proposed in the following list:

Ogren plant allergy scale, a qualitative/estimative method proposed by Ogren [61], considers subjectively different plant-specific criteria based on studies about similarities between allergenic and non-allergenic plants. Characteristics include pollen weight and size, pollen moisture, flower fragrance, and the position of male flowers in monoecious species. The scale categorises species at 10 levels, with one being non-allergenic and 10 being highly allergenic. No formula was created to calculate this index. This index refers to plants regardless of the vegetation composition in a space.

Allergen index, a graded method proposed by Hruska [63], is based on information about the plant's life cycle, the length of its phenanthestic period, the presence of phenomena of cross-reactivity (CR), and species abundance. The literature has described a specific formula to calculate this index [63]. This index includes the vegetation composition of a space. Some cities in Central Italy [70] and schoolyards in Novi Sad, Serbia [71], have been investigated using this index.

Allergenic potential of plants (GRADE approach) was assessed in Italy by Ortolani [72], based on the existence of scientific evidence and risks that pollen exposure causes hay fever symptoms and that pollen grains can cause allergic sensitisation. A committee of experts used a GRADE approach (Grading Recommendations, Assessment, Development, and Evaluation) to clarify the allergenicity of the species in the list as high, moderate, or low. The assessment is qualitative, and no formula has been described to calculate this potential.

Urban green zone allergenicity index (I_{UGZA}), a graded method proposed by Cariñanos [49], calculates the allergenic potential index of urban green spaces, and at first, it was applied in some Mediterranean cities. This index is expressed as a ratio and compares an existing green space with a hypothetical space with maximum allergenicity. The index is based on the following assumptions: Plants that mature with a higher crown volume emit higher quantities of pollen, anemophilous trees produce more pollen than other trees, and pollen release is directly proportional to the number of individuals belonging to one species [51]. This index is obtained through a specific formula [49, 73]. It includes the vegetation composition of a space. The potential allergenic value (PAV, or VPA) of each plant in a park is calculated based on three primary parameters: pollination strategy, also named PEs (initially on a 0–3 scale, later simplified to a 1–3 scale), assigning the minimum value to only female-sex individuals (later simplified to a minimum value = 1 for entomophilous plants) and the maximum value to anemophilous plants (value 3); potential allergenicity (ap, estimated on a 0–4 scale) that the species provoke in humans (estimated through specific bibliographies in medicine and public health), assigning the maximum value to *Betula*, *Alnus*, Poaceae, and *Artemisia*; and the duration of the pollination period or

principal pollination period (DPP or PPP, ranging from 1 to 3 weeks). The PPP for species in the first study was established based on published data for the flowering periods of standard Mediterranean species and the pollen calendar for the city of Granada, developed using daily mean pollen data for over 10 years. The PAV, given by the product of the three parameters, ranges from 0 to 36. Five classes of allergenicity have been defined: nil (PAV = 0), low (PAV from 1 to 6), moderate (PAV from 8 to 12), high (PAV from 16 to 24), and very high (PAV from 27 to 36). The I_{UGZA} depends directly on both the PAV of each species and the total volume of pollen-producing vegetation (mature individuals) and is inversely proportional to the total surface area of the park. The surface area occupied by each species was estimated from the maximum horizontal crown projection area (in m^2) for an adult individual, obtaining this information from published research into the standard size attained by species during reproductive maturity in a specific climate zone. To calculate the crown volume of vegetation, tree height was estimated as a cylinder, shrubs as hemispheres, and hedges as parallelepipeds (height $\times$ surface). The value to be obtained would thus lie between $I_{UGZA} = 0$ for spaces with no allergenicity and $I_{UGZA} = 1$ for spaces with maximum allergenicity. The threshold value (TV) of a park determining allergy symptoms has been observed when $I_{UGZA} = 0.3$. Several Mediterranean urban parks, starting from Garcia Lorca Park in Granada, Spain [13], the Mediterranean cities of Spain and Italy [74], three types of urban gardens in Poland [75], several metropolitan areas in Bratislava (Slovakia) [76], and the Macaronesian islands (Funchal City, Madeira) [77], have been investigated through this index.

I_{ISA} index, a graded system proposed by Jochner-Oette in 2018 [51], is similar to the previous one. Still, it considers the crown height and surface area individually measured for each plant (trees and shrubs), not based on a mean height or diameter attained at reproductive maturity, as in Cariñanos [73]. This index is obtained through a specific formula [51]. In Bratislava (Slovakia) [76], some areas have been investigated, such as designing a running index over time.

CARE-s index, a graded system, has been defined by Magyar as ‘the potential of a plant taxon to provoke allergy based on immunogenicity, pollen production, and morphology/pollination type’ [3]. The AC_p (the raw value of a plant’s allergenic potential) was proposed using Thommen’s postulates and two geographical factors (population size and the pollen season length). Geographically variable factors, such as differences among countries (ie, pollen concentration or population size), have been excluded from the parameters used in this system. This index is a product of three parameters: Im (Immunogenicity, based on the strength of evidence to cause allergy symptoms in patients, mainly found in the Allergome database [53] and references based on evidence); Mo (Morphology, evaluated as stamen morphology, pollen morphology, pollination strategy, and palynology from the literature); and Po (Pollen production, obtained from a horticultural collection of tree taxa common in urban street lines in the Pannonian biogeographical region). All parameters are not calculated but are instead estimated in three classes. Thus, potential allergenicity is defined as ‘the potential of a plant taxon to provoke allergy based on immunogenicity, pollen production, and morphology’. The CARE-s index is expressed in five classes of allergenic potential (ap) and a sixth class, ‘unknown’: non-allergenic (0), low (1), medium (2), high (3), and very high (4). The index is also available online, enabling users to make more straightforward calculations with their local plant taxa [77].

A regional guide for the allergenic potential of tree pollen is a method developed by De Weger in 2024 [78], based on six published classification guides, pollen sampling (using Hirst-type seven-day volumetric spore traps), and tests conducted on 467 patients at the hospital. The criteria for allergenic potential have been based on the literature, the amount of airborne pollen measured, and the sensibilisation levels found in the patients. The allergenicity of taxa in the Netherlands was classified into five classes (low or not available, weak, moderate, strong, and very strong) based on scientific evidence of symptom manifestation. This list considers the effects on the local population of some species considered low allergenic, which in other parts of the world result in highly allergenic reactions (eg, *Chamaecyparis lawsoniana*, *Taxodium distichum*, *Thuja*), probably due to climatic factors (some coniferous species cannot pollinate in places with a cold climate). To compare the classes of allergenic potential, see **Table 2**.

Other evaluations of the allergenic potential of plants have been investigated in the literature. For instance, the case of Beijing (China) has been studied through a survey and experts' interviews [79], which identified 99 pollen-allergenic plant species. Pollens were concentrated in March and April (trees) and from July to September (herbs). The case of the Mexico City Metropolitan Area (dry season 2012–2013), investigated using a Hirst-type trap sampler [67], shows that the most representative pollen types found at the three sites were, regardless of urbanisation levels: *Fraxinus*, Cupressaceae/Taxodiaceae, *Casuarina*, *Alnus*, Myrtaceae, and *Pinus*. Total pollen concentration was most significant in the moderately urbanised area, although earlier blooming occurred in the highly urbanised zone. In the medium–high urbanised site, pollen concentration was the lowest because there were few green areas. At several sites (more or less urbanised), the pollen peak emission occurred near midday or in the afternoon and evening, correlating with air temperature and relative humidity. A qualitative study of the relationship between monitored pollen and vegetation in some areas (Cordoba, Spain, and Ascoli Piceno, Italy) at a regional scale was proposed by Staffolani et al. [80]. In South Africa, the prevalence of airborne allergen sensitisation in a polluted area has been studied using skin prick testing and botanical studies [81]. The highest allergy prevalence was attributed to Poaceae (*Cynodon dactylon*, *Lolium perenne*, *Zea mays*), *Olea* (olive tree), and *Platanus* (plane tree). Other allergies were caused by weed mix: *Artemisia*,

Allergenicity level [72]	Classes and value of potential allergenicity (VPA) [73, 74]	Classes of allergenic potential [51]	CARE-s index [3]	Grade of allergenic potential [78]
Not allergenic or unknown	0	0	Unknown 0 (nonallergenic)	Low or not available
Low	1 ($1 \leq \text{VPA} \leq 6$)	1	1 (low)	Weak
Medium (or moderate)	2 ($8 \leq \text{VPA} \leq 12$)	2	2 (medium)	Moderate
High	3 ($16 \leq \text{VPA} \leq 24$)	3	3 (high)	Strong
Very high	4 ($27 \leq \text{VPA} \leq 36$)	4	4 (very high)	Very strong

Table 2.
Classification of allergenic potential and references (VPA = value of potential allergenicity) [3, 49, 72, 74, 78].

Chenopodium, Salsola, Plantago, and *Ambrosia*, underlining the strong impact of allergens from exotic plants. The effect was amplified by the simultaneous spread of airborne fungal spores (*Alternaria*, *Cladosporium*).

3.4 Possible applications of allergenic potential

The ap has been applied to assess the possibility and strength of plants in an urban park to provoke sensitisation or allergy in the population and to try to classify the urban green areas on an index with a scientific basis. The ap of green areas has been linked to a threshold value ($TV = 0.3$ in the case of IUGZA), giving the appearance of symptoms of allergy in several experimental studies on populations in different areas of the world and across different age groups. Several city parks in Mediterranean cities have been studied from this point of view. In assessing ap, limits and comparability of indexes are also published by Suanño [82]. In general, they were not compared or standardised over the same dataset. The expression of allergenicity using an index should be applied to green spaces with similar characteristics. In a study in the Botanical Garden of Bologna, Italy, the indexes IUGZA and IISA (also named SAI) have been compared, collecting vegetation data through systematic sampling and arboreal census in the same dataset. Thus, it was possible to compare them. The allergenic risk of the park was moderate to high, according to IISA, and very low, according to IUGZA. The first index does not consider the total volume of the crowns, so it was considered less reliable than the second, IUGZA, in evaluating the allergenic potential of a specific enclosed green space [82]. However, it must be considered that the current assessments of the ap of a specific local green area are based on the flora composition, the allergenicity of the plants in the green area, the height and surface occupied by the tree crown, but, based on the cited literature, not on the ap of pollen coming from other parts yet, which can also originate from long distances, carried by the prevailing winds. Thus, the real expression of allergy symptoms can also be influenced by ‘alien’ airborne pollens, depending on climate change [69], and only real-time airborne allergen monitoring can provide this information. Furthermore, the local evaluation of ap shows several differences in the values assigned to the same taxa. The diffusion may differ from place to place, so the amount of airborne pollen and its impact on people varies significantly. *Olea europaea* or *Chamaecyparis lawsoniana* have a completely different evaluation from Eastern Europe (Grade 1, low allergenic) to the Mediterranean area (Grade 4, very high allergenic). Despite this, it is important to calculate the ap of a park as a prediction of allergenicity and use it in green area planning to make cities healthier, smarter, and more liveable for people. In the future, possible applications of a.p. and plant pollen monitoring, including the pollen portion from long distances, are automated real-time monitoring of airborne allergens, forecasting and modelling of airborne allergens, and smartphone applications to mitigate the health impacts of airborne allergens [69].

4. Pollen allergy and CR

Cross-reactivity refers to an immunological phenomenon whereby an immune response to a given antigen causes reactivity towards other antigens structurally

similar to the inducing antigen [13, 83]. A protein can be considered capable of CR with other allergens if it shares at least 35% similarity with them. The greater the homology, the greater the risk of CR. The common view is that diet can promote the onset of pollen allergy. The opposite is true; in fact, some individuals with respiratory allergies also have adverse reactions to certain foods. The culprits are pan allergens, that is, allergens that are present in both plant pollen and some fruits and vegetables (but also some fish, such as shellfish) and that can give cross-allergies (thus due to the summation of environmental pollen exposure and food intake). There are about 10 pan allergens, but the most frequent are profilin, PR-10, and LTP. Profilin is found in most cells of all eukaryotic organisms. PR-10 (pathogenesis-related protein) is a group of pan allergens widely distributed in the plant kingdom. The family's progenitor is *Betula*, and its major allergen is Bet v 1. CR is most frequent among individuals allergic to birch and fruits belonging to the Rosaceae family, such as apple, apricot, pear, and cherry (homology > 50%) (Table 3). PR-10 are proteins characterised by marked sensitivity to both heat and the action of digestive juices. Therefore, PR-10, particularly abundant in fruit flesh, disappears with cooking. Lipid transfer proteins (LTPs) are proteins that are resistant to the action of digestive enzymes and heat, so cooking often does not resolve them, except for some vegetables such as asparagus, cabbage, and fennel, which, when boiled, lose LTPs by releasing them into the cooking water. The characteristic clinical syndrome of allergic individuals with CR to the above-mentioned foods is oral allergy syndrome. Immediate symptoms are local itching, palate and tongue burning, and swelling of the lips and oral mucosa. A sense of constriction in the pharynx and difficulty swallowing may be associated in severe cases. The phenomenon of CR is not an exclusive manifestation of pollinosis. Other respiratory allergens can trigger reactions to foods. The most characteristic example is the CR between dust mite (*Dermatophagoides pteronyssinus*) and shrimp; since a minor mite allergen, the Der p 10, belongs to the group of tropomyosins (pan allergens) found within the crustacean family in this case, reactions also occur with cooked food.

Pollen (scientific name of plants)	Vegetal food (common name)
Poaceae (sin. Gramineae)	Melon, watermelon, orange, kiwi, tomato, wheat, peach, apricot, cherry, plum, peanuts, cereals
<i>Artemisia</i> sp. (Asteraceae)	Melon, banana
Asteraceae (sin. Compositae)	Chamomile, celery, carrot, melon, watermelon, apple, banana, pumpkin
<i>Parietaria</i> (Urticaceae)	Mulberry, basil, peas
<i>Olea europaea</i> (Oleaceae)	Olive
<i>Betula</i> (Betulaceae)	Apple, peach, apricot, walnuts, hazelnuts, cherry, pear, banana, carrot, potato, fennel, celery, peanuts, almonds
<i>Corylus avellana</i> (Betulaceae)	Hazelnuts
<i>Ambrosia</i> (Asteraceae)	Banana, watermelon, melon, chamomile, pumpkin, celery

Table 3.
Examples of CR in Southern Europe.

5. Biodiversity and allergenic potential

Biodiversity is the basis for a healthy environment. Nature in cities has several benefits (ecosystem services), particularly regarding the urban climate: One of the most frequently mentioned benefits of urban parks is the reduction of the heat island effect. Some of the important reasons for enjoying a park include nice weather, comfortable wind flow, better temperature, and insulation compared to less natural areas of the city [84]. Vegetation filters air dust, removes pollution, provides natural sounds and smells, and, through evaporation and transpiration, reduces air moisture [75]. It also captures soil water, reducing the impacts of extreme weather events. Improving the contact between humans and nature is very important, especially in urban areas [85]. In cities, the urban jungle is the collection of trees, shrubs, and other plants that coexist with people (**Figure 5**). Despite this, unfortunately, plants can also cause disservices to human health. The falling of diseased or old trees or branches, the emission of biogenic volatile organic compounds into the air, the danger of toxic and poisonous plants, and the production of allergenic pollen [75] are some examples.

Several research studies have been conducted worldwide to identify the source of pollinosis or asthma caused by plants. In Japan (Tokyo city), taxonomic classification indicates multiple pollen sources, including natural forests, planted forests, roadsides, parklands, and horticultural activities. The most allergenic plant is Japanese cedar (*Cryptomeria japonica*) and other Cupressaceae species, peaking in mid-February to March [7]. This is one of the most allergenic plant families in different parts of the world and may originate from natural forests or anthropic plantations in parks and gardens. A plant may be allergenic in some areas but not highly allergenic in other parts of the world. Ginkgo (*Ginkgo biloba*), a very ancient



Figure 5.

A location in a historic courtyard, showing a high level of biodiversity and several phenological aspects (photo by F. Marinangeli).

and beautiful tree often cultivated in gardens in Japan, is considered one of the most allergenic pollen sources there because it is very widespread. In other parts of the globe, where Ginkgo is sporadically cultivated in parks, such as in Italy [72], Spain [86], the Netherlands [78], and Hungary [3], it is considered a low-to-moderate allergenic plant. Additionally, the olive tree (*Olea europaea*), one of the most impactful allergenic plants in the Mediterranean area [73], the elective range of the species, has a lower allergenic potential in Eastern Europe [3].

Tree selection decisions (choosing the right family, genera, species, variety, or planting female individuals of dioecious species in parks, see [61]) can effectively reduce airborne pollen [6]. Urban green space planners should consider planting more non-allergenic trees and improving public pollen information and warning systems [87]. The criterion of high biodiversity in greenery systems should always be used. This means a high number of different species and few individuals of each species, high biodiversity (number of species), female individuals of dioecious species (with zero allergenic potential), and less impact of allergenic pollen on citizens. In green space planning, many professional skills are required in collaboration. Optimising existing knowledge sets and encouraging the integration of interdisciplinarity can facilitate the functions of biodiversity needed for sustainable urban landscapes [88].

5.1 The most allergenic plants

Several scientific studies show some plant lists based on qualitative or quantitative evaluations of allergenic potential. In Italy, a 100-plant list (trees and shrubs) was produced in 2015 [72]. This list was updated by Cariñanos and Marinangeli in 2021 [74], where the specific allergenicity of 150 urban trees and shrubs was assessed. In cases where a different value from those already assigned by the previous authors was obtained, it was agreed to apply the most conservative criterion, that is, to maintain the value most supported by scientific evidence. The airborne pollen in Granada (concentration and time) was studied using a biological particulate matter sampler [51, 73]. A database was generated in which groups of trees were assigned a value rated in five classes (nil, low, moderate, high, and very high). Other studies have especially investigated the most commonly used ornamental plants or trees. In particular, a recent study [78] consulted six published classification guides that classified the allergenicity of tree pollen for different regions. It adopted a five-class classification used in the Netherlands, with the following values: low or not available, weak, moderate, strong, and very strong. Additionally, a comprehensive work published in the literature [3] adopted a five-class system based on similar parameters to those used by Cariñanos [73, 74]. It is impossible to express all the plant lists here. Still, it is possible to collect data obtained through a cross-control of several reference sources, grouping plants with allergenic pollen into three main risk classes to provide useful information to doctors and patients (**Table 4**). The plants have been checked in the lists, and the allergenic potential (ap) value has been reported in the third column. In the IUIS allergen database, all types of allergens have been investigated. Wherever possible, subspecies levels have been detailed to the greatest extent found in the literature, since some ornamentals are single-sex clones or sterile plants, which may be relevant when establishing their allergenic capacity.

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
<i>Acer negundo</i>	Tree	Very high/high/medium	NF
<i>Alnus × spaethii</i>	Tree	Very high	NF
<i>Alnus glutinosa</i>	Tree	Very high/high	Yes
<i>Alnus incana</i>	Tree	Very high/high	NF
<i>Ambrosia artemisiifolia</i>	Herb	Very high	Yes
<i>Ambrosia trifida</i>	Herb	Very high	Yes
<i>Betula alba</i>	Tree	Very high	NF
<i>Betula ermanii</i>	Tree	Very high	NF
<i>Betula papyrifera</i>	Tree	Very high	NF
<i>Betula pendula</i>	Tree	Very high	Yes
<i>Betula pubescens</i>	Tree	Very high	NF
<i>Betula utilis</i>	Tree	Very high	NF
<i>Broussonetia papyrifera</i> , (male)	Tree	Very high/low	Yes
<i>Carpinus betulus</i>	Tree	Very high/medium	Yes
<i>Castanea sativa</i>	Tree	Very high/high/medium/null	Yes
<i>Casuarina equisetifolia</i>	Tree	Very high/high/medium	NF
<i>Chamaecyparis lawsoniana</i>	Tree	Very high/low/null	NF
<i>Corylus avellana</i>	Tree	Very high/high/low	Yes
<i>Cryptomeria japonica</i>	Tree	Very high	Yes
<i>Cupressocyparis leylandii</i>	Tree	Very high/medium/null	NF
<i>Cupressus arizonica</i>	Tree	Very high	Yes
<i>Cupressus macrocarpa</i>	Tree	Very high	NF
<i>Cupressus sempervirens</i>	Tree	Very high/medium	Yes
<i>Dyospiros kaki</i>	Tree	Very high/low	NF
<i>Fagus sylvatica</i>	Tree	Very high/high/medium	Yes
<i>Fraxinus excelsior</i>	Tree	Very high/high/medium	Yes
<i>Hesperocyparis macrocarpa</i>	Tree	Very high	NF
<i>Juglans nigra</i>	Tree	Very high/high	Yes
<i>Juniperus communis</i>	Shrub	Very high/high/medium/low	NF
<i>Juniperus phoenicea</i>	Shrub	Very high	NF
<i>Juniperus virginiana</i> , (male)	Shrub	Very high	Yes
<i>Ligustrum vulgare</i>	Shrub	Very high/high/medium/low	Yes
<i>Metasequoia glyptostroboides</i>	Tree	Very high/null	NF
<i>Morus nigra</i>	Tree	Very high/low	Yes
<i>Olea europea</i>	Tree	Very high/high/medium	Yes
<i>Ostrya carpinifolia</i>	Tree	Very high/high/medium	Yes
<i>Parietaria</i>	Herb	Very high/high/medium	Yes
<i>Platanus acerifolia</i>	Tree	Very high/high	Yes
<i>Platanus orientalis</i>	Tree	Very high	Yes

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
<i>Platanus x hispanica</i>	Tree	Very high/high	Yes
<i>Platycladus orientalis</i>	Shrub	Very high/medium	NF
<i>Podocarpus neriifolius</i> , (male)	Tree	Very high	NF
<i>Populus deltoides</i>	Tree	Very high	NF
<i>Taxodium distichum</i>	Tree	Very high/high/medium/null	NF
<i>Taxus baccata</i> , (male)	Shrub	Very high/high/medium/null	NF
<i>Tetraclinis articulata</i>	Shrub	Very high	NF
<i>Thuja plicata</i>	Tree	Very high/low	NF
<i>Ailanthus altissima</i> , (male)	Tree	High/medium	NF
<i>Alnus cordata</i>	Tree	High	NF
<i>Araucaria</i> spp	Tree	High	NF
<i>Carya</i> spp	Tree	High	Yes
<i>Cedrus atlantica</i>	Tree	High/medium/null	NF
<i>Chamaecyparis nootkatensis</i>	Tree	High	NF
<i>Chamaerops humilis</i>	Tree	High/medium	NF
<i>Corylus colurna</i>	Shrub	High	NF
<i>Fraxinus ornus</i>	Tree	High/medium	NF
<i>Ginkgo biloba</i> , (male)	Tree	High/medium/low/null	NF
<i>Juglans regia</i>	Tree	High	Yes
<i>Ligustrum sinensis</i>	Shrub	High	NF
<i>Ligustrum lucidum</i>	Shrub	High	NF
<i>Liquidambar styraciflua</i>	Tree	High/medium/null	NF
<i>Morus alba</i>	Tree	High/medium/low	Yes
<i>Nothofagus antarctica</i>	Tree	High	NF
<i>Pinus sylvestris</i>	Tree	High	NF
<i>Populus alba</i> ‘Pyramidalis’	Tree	High/medium	NF
<i>Populus nigra</i> ‘Italica’	Tree	High/medium	Yes
<i>Populus</i> spp, (male)	Tree	High/medium/low	NF
<i>Quercus ilex</i>	Tree	High/medium	Yes
<i>Quercus petraea</i>	Tree	High/medium	NF
<i>Quercus robur</i>	Tree	High/medium	NF
<i>Salix alba</i>	Tree	High/low	NF
<i>Salix purpurea</i>	Tree	High	NF
<i>Ulmus minor</i>	Tree	High/medium	NF
<i>Ulmus pumila</i>	Tree	High/medium	NF
<i>Acacia dealbata</i>	Tree	Medium/low	NF
<i>Acer griseum</i>	Tree	Medium/low	NF
<i>Acer monspessulanum</i>	Tree	Medium/low	NF
<i>Acer pensylvanicum</i>	Tree	Medium/low	NF

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
<i>Acer platanoides</i>	Tree	Medium/low	NF
<i>Acer pseudoplatanus</i>	Tree	Medium/low	NF
<i>Acer rubrum</i>	Tree	Medium/low	NF
<i>Acer saccharinum</i>	Tree	Medium	NF
<i>Aesculus hippocastanum</i>	Tree	Medium/low	Yes
<i>Aesculus x carnea</i>	Tree	Medium	NF
<i>Agrostis stolonifera</i>	Herb	Medium	NF
<i>Alopecurus pratensis</i>	Herb	Medium	NF
<i>Amaranthus caudatus</i>	Shrub	Medium	NF
<i>Amaranthus retroflexus</i>	Shrub	Medium	Yes
<i>Anthoxanthum odoratum</i>	Herb	Medium	Yes
<i>Artemisia vulgaris</i>	Herb	Medium	Yes
<i>Atriplex hortensis</i>	Herb	Medium	NF
<i>Atriplex tatarica</i>	Herb	Medium	NF
<i>Callistemon spp</i>	Shrub	Medium	NF
<i>Calocedrus decurrens</i>	Tree	Medium	NF
Cannabaceae	Herb	Medium	Yes
<i>Cedrus deodara</i>	Tree	Medium	NF
<i>Cedrus libani</i>	Tree	Medium	NF
<i>Celtis australis</i>	Tree	Medium	NF
<i>Celtis occidentalis</i>	Tree	Medium	NF
<i>Cephalotaxus drupaceae</i>	Shrub	Medium	NF
<i>Cercidiphyllum japonicum</i>	Tree	Medium	NF
<i>Chenopodium album</i>	Herb	Medium	Yes
<i>Cynodon dactylon</i>	Herb	Medium	Yes
<i>Dactylis glomerata</i>	Herb	Medium	Yes
<i>Eucalyptus chamaldulensis</i>	Tree	Medium/low	NF
<i>Eucalyptus globulus</i>	Tree	Medium	NF
<i>Eucommia ulmoides</i>	Tree	Medium	NF
<i>Eupatorium capillifolium</i>	Herb	Medium	NF
<i>Festuca rubra</i>	Herb	Medium	NF
<i>Fraxinus americana</i>	Tree	Medium	NF
<i>Fraxinus angustifolia</i>	Tree	Medium	NF
<i>Fraxinus pennsylvanica</i>	Tree	Medium	NF
<i>Holcus lanatus</i>	Herb	Medium	Yes
<i>Humulus japonicus</i>	Herb	Medium	Yes
<i>Humulus lupulus</i>	Herb	Medium	NF
<i>Iva xanthiifolia</i>	Herb	Medium	NF
<i>Larix decidua</i>	Tree	Medium/null	NF

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
<i>Lolium perenne</i>	Herb	Medium	Yes
<i>Melaleuca cajuputi</i>	Tree	Medium	NF
<i>Mercurialis annua</i>	Herb	Medium	Yes
<i>Parietaria judaica</i>	Herb	Medium	Yes
<i>Parthenium hysterophorus</i>	Herb	Medium	Yes
<i>Phleum pratense</i>	Herb	Medium	Yes
<i>Phoenix canariensis</i>	Tree	Medium/low	NF
<i>Phoenix dactylifera</i>	Tree	Medium	Yes
<i>Picea abies</i>	Tree	Medium/low/null	NF
<i>Picea omorika</i>	Tree	Medium/low	NF
<i>Picea pungens</i>	Tree	Medium	NF
<i>Pinus halepensis</i>	Tree	Medium	NF
<i>Pinus nigra</i>	Tree	Medium	NF
<i>Pinus pinaster</i>	Tree	Medium	NF
<i>Pinus pinea</i>	Tree	Medium	Yes
<i>Pistacia atlantica</i>	Tree	Medium	NF
<i>Pistacia vera</i>	Tree	Medium	Yes
<i>Plantago lanceolata</i>	Herb	Medium	Yes
<i>Poa</i> spp	Herb	Medium	Yes
<i>Podocarpus macrophyllus</i>	Tree	Medium	NF
Polygonaceae	Herb	Medium	NF
<i>Populus tremula</i>	Tree	Medium	NF
<i>Populus x canadensis</i>	Tree	Medium/low	NF
<i>Prosopis cineraria</i>	Tree	Medium	NF
<i>Prosopis juliflora</i>	Tree	Medium	Yes
<i>Pterocarya fraxinifolia</i>	Tree	Medium/null	NF
<i>Quercus cerris</i>	Tree	Medium	NF
<i>Quercus frainetto</i>	Tree	Medium	NF
<i>Quercus imbricaria</i>	Tree	Medium	NF
<i>Quercus palustris</i>	Tree	Medium	NF
<i>Rumex crispus</i>	Herb	Medium	NF
<i>Salix caprea</i>	Tree	Medium	NF
<i>Sambucus nigra</i>	Shrub	Medium/low/null	NF
<i>Schinus terebinthifolius</i>	Tree	Medium	NF
<i>Secale cereale</i>	Herb	Medium	Yes
<i>Sequoia sempervirens</i>	Tree	Medium	NF
<i>Sequoiadendron giganteum</i>	Tree	Medium	NF
<i>Solidago canadensis</i>	Herb	Medium	NF
<i>Solidago virgaurea</i>	Herb	Medium	NF

Plant source of allergenic pollen	Mtype	Allergenic potential class	IUIS
<i>Styphnolobium japonicum</i>	Tree	Medium	NF
<i>Syringa vulgaris</i>	Shrub	Medium	Yes
<i>Tamarix ramosissima</i>	Tree	Medium/null	NF
<i>Thuja occidentalis</i>	Tree	Medium	NF
<i>Tilia cordata</i>	Tree	Medium	NF
<i>Tilia henryana</i>	Tree	Medium	NF
<i>Tilia insularis</i>	Tree	Medium	NF
<i>Tilia mongolica</i>	Tree	Medium	NF
<i>Tilia neglecta</i>	Tree	Medium	NF
<i>Tilia platyphyllos</i> 'Rubra' or 'Corallina'	Tree	Medium	NF
<i>Tilia tomentosa</i>	Tree	Medium	NF
<i>Tilia x euchlora</i>	Tree	Medium	NF
<i>Tilia x europaea</i>	Tree	Medium	NF
<i>Trachycarpus fortunei</i>	Tree	Medium	NF
<i>Typha</i> spp	Herb	Medium	NF
<i>Ulmus americana</i>	Tree	Medium	NF
<i>Ulmus glabra</i>	Tree	Medium	NF
<i>Ulmus laevis</i>	Tree	Medium	NF
<i>Urtica dioica</i> , (male)	Herb	Medium	NF
<i>Vitis vinifera</i>	Liana	Medium	Yes
<i>Wisteria sinensis</i>	Shrub	Medium	NF
<i>Zea mays</i>	Herb	Medium	Yes
<i>Zelkova serrata</i>	Tree	Medium/null	NF

Plants' source of allergenic pollen: family, genus, species, variety, or hybrid (scientific name).
Mtype (Morphotype): tree, shrub, herb, liana.
Allergenic potential class: Very high (4); High (3); Medium (2); Low (1); Null (0).
IUIS; Allergen found in database WHO-IUIS (Yes if present; NF if not found): All possible types of allergens have been investigated (food, contact, pollen, airborne, injection).

Table 4.

The main plant source of allergenic pollen and their allergenic potential for humans [3, 51, 72–74, 78]. Red colour describes plants with very high or high value of allergenic potential, while orange colour indicates plants with medium allergenic potential.

5.2 Green areas and their impact on respiratory health

The morphology of green space and human health are related [89], so it is essential to design green areas to enhance health outcomes. Plant species used for ornamental purposes in urban landscapes (parks, gardens, tree alignments, or open green spaces in a broad sense) are the most common cause of pollen allergies among the local population [49]. Health-promoting green area planning should be integrated into epidemiological research, which shows many allergy symptoms related to pollination periods, the number of individuals of a species, biodiversity, wind, and other climate factors. Therefore, it is essential in green planning and

plantations to consider the plant list to exclude (species with a high or very high allergenic potential), the plant list to include only a few individuals (species with a moderate allergenic potential), and the plants without restrictions (species with a low allergenic potential). When designing green areas, balsamic plants, such as conifers with low allergenic potential, that have a positive effect on respiratory health should also be taken into consideration.

5.3 Selection of relevant plant species in the context of urban environments

The selection of plants, from the point of view of allergenic potential, should focus on some fundamental points for an urban green design that respects human health.

5.3.1 The choice of species in urban greening

The choice of species should take into account multiple factors: the sexuality of the plant and of the individual to be planted. There are monoecious plants with hermaphroditic flowers or dioecious plants (eg, *Ginkgo*), where the sexes are separate on different individuals, or the male and female flowers are distinct on the same individual. Since pollen is only emitted by male flowers, female plants can be chosen to avoid the emission of airborne allergens. In species with hermaphroditic flowers, that is, with male and female parts on the same flower, or conifers with male and female cones on the same individual, it is necessary to take into account the allergenic potential of the species (or variety) published in some works, which are constantly updated [3, 49, 72, 74, 78]. In this chapter, the lists of the most commonly used species are published, which should instead be limited due to their high allergenic potential (**Table 4**). In this case, only a small number of such individuals should be foreseen in urban green areas.

5.3.2 Biodiversity

The aspect of biodiversity is fundamental to obtaining benefits both for the urban ecosystem environment and for humans. In fact, a high biodiversity index, determined by the number of different species in a green system, the diversity of biological forms (shrubs, herbs, trees, bulbous plants, etc.), chorological types (the main origin and best distribution area of the species), and the flowering and fruiting periods of the species, provides food to urban fauna (lepidoptera, hymenoptera, other insects, earthworms, birds, bats, and so on) and avoids monoculture systems where the same species is repeated in an artificial pattern. A highly biodiverse plant system (which we could define as ‘bio-diverse greenery’) imitates, reproduces, and restores the potential natural environment of the place. In this sense, as is known from scientific conferences (personal reference of Prof. Carlo Blasi, Italy), it is useful to consult maps, where available, of the potential vegetation of the place and of the vegetation dynamics. This involves selecting, first, the shrubs of the dynamic succession that will lead to the formation of the forest, ensuring optimal rooting and a natural evolution of the green system. From an allergenic point of view, it is both possible and advisable to avoid planting species with very high allergenic potential, particularly if they are non-native, and to select species with medium–low allergenic potential [87]. Planting very few

individuals among the allergenic species and more individuals of harmless species can help ensure the future healthiness of greenery for the urban population, which includes vulnerable groups such as fragile individuals, athletes, children, the elderly, and even pets, who may be more exposed to allergenic risks.

5.4 Selection of relevant plant species in reforestation efforts

In forestry interventions, in semi-natural or natural environments, the population density is much lower; therefore, the impact of allergenic pollens on the human population is also much lower at an epidemiological level. However, if the interventions concern semi-inhabited areas or areas close to cities (eg, green belts or other nature-based solutions), it is necessary to take into account the direction of the prevailing winds and implement a choice based on biodiversity and low allergenic potential, as expressed in the previous paragraph. In this case, the choice of native species that are well-adapted to the local geopedological and climatic environment will determine better rooting of the species, with better vigour and capacity to colonise the environment. In some historical periods, some pioneer forestry species, such as Cupressaceae, have been overused. Today, in light of discoveries regarding their very high allergenicity, determined by a long pollen season (eg, *Cupressus*, January–April, in the Northern Hemisphere), they should be avoided as much as possible. In their replacement, taking into account the positive aspects of the balsamic substances emitted and useful for air purification, other conifers (*Cedrus*, *Pinus*, *Abies*, *Picea*) can be used, which have medium–low allergenicity but, above all, a reduced pollen season (15–30 days, depending on the climate and location) [72, 74, 87].

5.5 Implications of invasive species and globalisation of the flora

The diffusion of invasive alien plant species (IAPS) across the globe indirectly impacts human health, causing reduced native plant diversity and increased exposure to air pollution [90]. In some cases, the spread of IAPS can have significant and direct implications for allergology. The considerable airborne pollen diffusion of *Ambrosia* (ragweed), one of the main allergenic genera in the world, in Asia, Australia, Africa [91], or Europe [92] from the Adriatic East Coast, is a typical example. Additionally, the spread of certain species from the highly allergenic Asteraceae family (such as ornamental daisies) significantly impacts respiratory health in urban areas. *Senecio inaequidens* (**Figure 6**) also known as South African ragwort, for example, is transported by animals, wind, and motorised rubber-wheeled vehicles, making it widespread along main roads, railways, pastures, and gardens in South Africa (its native country), other parts of Africa, and several regions of the world, such as the Canary Islands, Europe [93], and Korea [94]. The pollen of this species is toxic in honey, and the plant is dangerous in fodder, being lethal to animals (eg, horses and rabbits) because it contains pyrrolizidine alkaloids. Its pollen can also be allergenic due to the high allergenic potential of the family. The potential ecological risk includes its ability to expand its range and invade various habitat types, from coastal regions to mountainous areas. Managing and controlling invasive species in urban green areas, roadsides, and railways is equally essential.



Figure 6.
Senecio inaequidens, an invasive plant whose pollen can cause toxicity in honey (photo by F. Marinangeli).

5.6 Implications of climate change

Over the past century, the air temperature has increased due to the impact of anthropogenic climate change, and an alteration in the air mixture has occurred [Kim, 2024]. Consequently, human exposure to organic and inorganic compounds, irritants to respiratory health, has increased [66, 95]. The impacts of climate change on pollen seasonality have been the topic of many studies. Climate change has been observed to affect the seasonality, production, atmospheric concentration, and geographic distribution of airborne pollen [69, 96, 97]. Pollen granules are part of the particulate matter PM₁₀: The warmer air and increased carbon dioxide have produced a more extended pollen period [98]. The start date of pollination, the date of maximum pollination, the end date, the pollen concentration, and the duration of the pollen season are influenced by climate change [69]. Some groups of the main allergen taxa have been studied: The Poaceae (grass) family and *Quercus* (oak) over the 26 years (1995–2020) have shown an advance in the start date of pollination; *Betula* has not exhibited the same reaction [99], probably due to the autecology of the genus, which is typical of temperate northern zones. The increasing pollen season duration in Northern Europe has been estimated at 0.9 days per year on average, and in 17 locations in the Northern Hemisphere, trees grown at elevated CO₂ concentrations produced substantially more pollen [100]. Another study of the impacts of climate change on PE in the United States by the end of the century found that temperature and precipitation alter daily PE maxima by 35% to 40%, and the change in phenology and temperature-driven pollen production increases the annual total PE by 16–40%. The increasing atmospheric CO₂ may increase pollen production, which, in conjunction with climate, increases end-of-century emissions by up to 200% [101]. Climate change can modify the epidemiology of viral infections, and coexposure to airborne pollen has enhanced human susceptibility to severe acute respiratory syndrome coronavirus infections, as verified in 130 monitoring stations in 31 countries across the globe [102]. The results of this study

show that airborne pollen, sometimes in synergy with humidity and temperature, explained, on average, 44% of the infection rate variability. Outside of lockdown, an increase in pollen abundance by 100 pollen/m³ resulted in a 4% average increase in infection rates.

Urban heat island intensity can disturb flowering periods and pollen concentrations, mainly in highly urbanised areas, as shown in a study in Mexico City [67], due to increased air temperature.

5.7 Biodiversity, air pollution, and pollinosis

Pollen granules, exposed to more polluted air, express greater allergenicity in humans from all world regions [98]. Climate, land-use change, and air pollution are expected to promote the spread of some invasive species, increase airborne pollen concentrations (eg, Ambrosia or ragweed), extend the pollen season, encourage long-distance transport of pollen or subpollen particles containing allergens [92], and contribute to increasing pollen allergenicity. Epidemiological studies suggest a potential link between the rising global prevalence of allergic diseases and increased air pollution [91]. Several pollutants can combine with climatic changes to enhance the expression of allergenic proteins in various pollen grains [103]. Pollen sensitisation is increased by exposure to contaminants for 24 to 48 hours. The pollutants make the exine surface more fragile, triggering a mucosal reaction and exposing it to pollen allergens. Pollutants also act as adjuvants to pollen allergens, leading to a greater production of IgE [1]. Educational aspects are also important: it is possible to study respiratory allergic diseases through digital technologies (eg, online platforms) to collect patient data (such as daily allergy symptoms) and improve diagnostic precision [104].

6. Plants as food and allergy for humans

Recently, there has been a growing interest in plant-based, ecologically more sustainable food education. However, food proteins from plants can cause severe allergies in humans. Plant-based products expose consumers to new sources of allergens through *de novo* sensitisation or cross-reactions with homologous allergens [105]. Some emerging allergens must be considered for control, management, and labelling to inform consumers. In the food industry, the new use of plant protein isolates or hydrolysates (especially from the Fabaceae family or pulses) increases the evidence of allergic, neo-allergic, and cross-allergic reactions, as described in western countries [106]. Therefore, emerging allergens must be considered for control, management, and labelling to inform consumers. In the food industry, the new use of isolated or hydrolysed plant proteins (especially those of the Fabaceae or legume family) increases the evidence of allergic, neo-allergic, and cross-allergic reactions, as described in western countries [106]. Allergen databases are essential for doctors and researchers to disseminate knowledge, as reported in [53]. All food allergens are shown. In the main group of foods, many fresh fruits (*Actinidia*, *Fragaria*, *Ananas*, *Prunus*, *Ziziphus*, and others) or vegetables (*Brassica*, *Cucurbita*, *Solanum*, and others), several cereals (wheat, rye, maize), legumes (*Cicer*, *Glycine*, *Lens*, *Pisum*, *Vigna*, and others), nuts, dried fruits, or seeds (*Arachis*, *Carya*, *Castanea*, *Corylus*, *Juglans*, *Macadamia*, *Pinus*, *Pistacia*, *Prunus dulcis*, *Sesamum*,

Ricinus, and others), spices, tubers, and roots (*Manihot*, *Panax ginseng*, *Solanum*) are potentially allergenic. Some examples of allergenic proteins in plant foods are the seed storage proteins (SSPs), which are essential in plants for development and defence and are present in nuts, seeds, and legumes; SSPs can be responsible for severe systemic reactions. In *Macadamia* nuts, a specific legumin (Mac I 2) has been isolated, and in pumpkin seeds (*Cucurbita* seeds), the Cuc ma 4. Also, the 2S Albumins SSPs can produce allergic reactions in humans. They have been isolated from *Cucurbita* seeds and flaxseeds (*Linum*). The most crucial food allergens in the Mediterranean are the LTPs, isolated from narrow-leaf lupine (*Lupinus*). The allergen Pru du 1061 has been isolated from almonds (*Prunus dulcis*) [58]. The uploaded list of allergenic food plants in [52], simplified into eight leading groups of foods, is available online.

To complete the topic, a few cases of anaphylaxis caused by vegetal foods are mentioned. An analysis of 100,000 human cases shows that the frequency of anaphylaxis is about 0.5–2%, especially in children and adolescents [107]. Reactions to peanuts and tree nuts were studied in the USA by Furlong in 2001 [108]. Out of 706 subjects in restaurants or ice cream and pastry shops, 156 episodes (29 first-time reactions) were recorded: Most reactions were caused by peanuts (67%), nuts (24%), a combination thereof, or were unknown (9%). Symptoms started within an average of 5 minutes after exposure and were severe in 27% of reactions. The food was not visually identifiable in 50% of these cases (eg, in sauces, condiments, spring rolls, etc.). In 23 cases, exposures were reported due to contamination during cooking or serving.

7. Some plants giving benefits to human respiratory health

Some plants are known in traditional medicine and healthy urban greening as applicable to respiratory health. In literature, several interesting examples of them have been tested, some of which are presented here. A group of tree plants with balsamic benefits is that of Coniferae (conifers), due to the presence, on the buds, leaves, and bark, of resins, monoterpenes (such as pinene), and essential oils that are diffused into the forest atmosphere. However, considering the allergenic potential of some of them, also used in urban parks, it is necessary to distinguish the period in which conifers pollinate from that in which they bring benefits to respiratory health, inviting park users to differentiate their behaviour in the different seasons of the year. The least impacting conifers for respiratory health are *Pinus* and *Cedrus*, compared to *Cupressus*, *Thuja*, and *Chamaecyparis*, which have a high allergenic potential. Also, *Eucalyptus* is a balsamic plant, often used in temperate-warm climates as a windbreak on marine and ocean edges. The leaves are steam-distilled to extract eucalyptus oil (eucalyptol or cineole), with therapeutic, perfumery, flavouring, and antimicrobial properties. As regards herbaceous and shrubby plants, we cite *Borago officinalis* (ubiquitous), extract against asthma [109]; seed oil, anti-leukotriene generation in mild asthma patients [110]; *Campanula trachelium* (Korean endemic plant), callus extract against asthma, tonsillitis, and sore throat [111]; *Cyclamen*, extract against rhinosinusitis [112]; *Daphne*, extract against atopic dermatitis and asthma [113]; *Gentiana olivieri*, extract with anti-inflammatory and immunomodulatory effects [114]; *Gentiana rigescens* (Dian long Dian in southern Yunnan, China), phenolic extract with anti-inflammatory and anti-allergy effects

[115]; *Hedera helix*, *Althaea officinalis*, *Drosera rotundifolia*, *Grindelia*, *Hedera helix*, *Pelargonium sidoides*, *Sambucus nigra*, and *Thymus vulgaris* extracts, effects on post-viral acute cough [116]; *Hedera helix* (ubiquitous, ivy), leaves dry extract: children with mild uncontrolled asthma despite regular inhaled corticosteroid therapy might benefit from an additional treatment with ivy leaves dry extract [117]; and *Thymus* (Moroccan *thymus*), essential oils with anti-inflammatory and anti-cyanobacterial effects [118]. The presence of secondary metabolites with favourable properties in treating respiratory diseases is evidenced in scientific literature [101, 117, 119–121], and many more examples could be found.

8. Conclusions

Pollen enables the reproduction of plants and photosynthetic autotrophic organisms, which are essential for life on the planet. Plants, whether integrated into urban green spaces or forestry around the perimeters of cities and inhabited centres, serve as a source of food and nutritional supplements for humans. However, they sometimes pose risks of allergies while often being beneficial for the respiratory system. The dispersion of pollen into the atmosphere, combined with air pollution, can significantly impact the human respiratory system. This allergenic potential varies according to several factors and has been thoroughly evaluated in the scientific community. Disseminating knowledge on this subject is urgent and must be as widespread as possible to reach all experts who engage in this field: doctors, allergists, researchers, botanists, green designers, patients, and ordinary citizens. For this reason, evaluating the allergenic potential of plants is crucial to planning healthy green areas, reducing the risk of exposure to allergens, and benefiting citizens. The degree of allergenic potential is already known for hundreds of plant taxa, primarily cultivated trees and shrubs [122, 123]. However, minor and spontaneous species, which are not cultivated in urban parks, remain understudied [124]. Furthermore, significant advancements can arise from new technologies that support automatic, computerised readings of pollen recorded by pollen samplers, enabling real-time pollen bulletins. Seasonal weather variations caused by global climate change influence the duration of pollen seasons, plant growth, and pollen allergenicity [125, 126]. Consequently, the design strategies for green spaces and reforestation facilities near cities and towns must account for these increasingly prominent aspects of allergology [127, 128–131].

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Conflict of interest

The authors declare no conflict of interest.

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In an age of rapid urbanization and intensifying climate change, cities face profound environmental challenges, including urban heat islands, deteriorating air quality, biodiversity loss, increased flooding risks, and diminished human well-being. Urban greening and reforestation emerge as vital nature-based solutions to build resilient, sustainable, and livable urban ecosystems. This open-access volume, *Urban Greening and Reforestation*, compiles cutting-edge research and practical insights from leading international experts in urban ecology, plant science, forestry, environmental planning, and related fields. Edited by Khalid Rehman Hakeem, Professor of Biological Sciences at King Abdulaziz University, Jeddah, Saudi Arabia, a distinguished researcher with extensive expertise in plant stress physiology, biotechnology, and phytoremediation, the book presents a multidisciplinary perspective on transforming urban landscapes. The chapters investigate innovative strategies such as large-scale urban afforestation, mangrove rehabilitation in coastal urban areas, vertical greening systems including green roofs and walls, integration of native species to enhance biodiversity, ecosystem-based adaptation for climate resilience, community-driven initiatives, and green infrastructure planning. These approaches not only mitigate carbon emissions, purify air, manage stormwater, and provide cooling effects but also support wildlife habitats, improve mental and physical health for residents, and promote social equity in green space access. While acknowledging persistent challenges, such as limited land availability, funding constraints, maintenance requirements, species selection in harsh urban conditions, and ensuring equitable distribution, the book emphasizes interdisciplinary collaboration, policy integration, community engagement, and adaptive management to overcome barriers and achieve long-term success. Ultimately, this work serves as a comprehensive resource for policymakers, urban planners, researchers, landscape architects, and practitioners, offering evidence-based guidance to advance greener, healthier, and more equitable cities in alignment with global sustainability goals.

*Usha Iyer-Raniga,
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